Neutron-Neutron, Proton-Proton and Neutron-Proton Interferometry in 30A MeV $^{40}Ar + ^{197}Au$ Collisions.

CHIC collaboration

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Small angle pp- and nn correlation functions from 30A MeV $^{40}Ar + ^{197}Au$ reactions exhibit the shape expected from quantum symmetrization effects and nuclear + Coulomb (pp) final-state interaction as predicted by BUU and evaporation calculations. The np function shows less correlation strength than expected. This may be due to Coulomb repulsion on the proton and/or to a population of the $S = 1$ spin state higher than expected. Selecting high energy nucleons strengthens the np and pp correlations.

The initial phase of a 30A MeV heavy ion reaction is normally binary. An asymmetric reaction, like ^{40}Ar + ^{179}Au, leads normally to incomplete fusion[1,2] followed by (fission +) evaporation[3]. In addition pre-equilibrium emission occurs from a statistical process[4] in hot regions and/or from quasi-elastic scattering.

In this paper we present small angle nn-, np- and pp correlations and compare them to predictions from fermion interferometry calculations. If the emission time is long a dominating anti-correlation is expected for small relative pp or nn momenta ($q = 1/2|\vec{p}_1 - \vec{p}_2|$) due to the anti-symmetrization of the two-fermion wave function. This should be characteristic for reactions where evaporation from a compound nucleus is the only source of particle emission[5]. Pre-equilibrium processes should on the other hand probe final state effects, i.e. the short range attractive nuclear interaction and the long range Coulomb interaction. In order to isolate the nuclear part, np correlations ought to be favourable since nn pairs are affected by Pauli exclusion and pp pairs also by mutual Coulomb scattering. A review over fermion interferometry in general is found in ref.[6].

The experimental arrangement has been presented in ref.[7]. Currents of 1 - 10 nA of a 30A MeV ^{40}Ar beam from the SARA two-cyclotron system at ISN, Grenoble, bombarded 3 mg/cm^2 CH_2, C and Au targets. Every second beam burst was suppressed, giving 166 ns between the bursts which corresponds to the time-of-flight of a 2.3 MeV neutron. The burst width was 1.5 ns which gives an energy resolution in the tof measurements, $\Delta E/E < 5\%$ for neutrons. In this paper we report on results from Ar + Au collisions where a target-out measurement showed a background of accepted nucleons due to false interactions of 5%.

Six cylindrical and five hexagonal liquid scintillators (Bicron BC-501) with a thickness of 15.6 cm and diameters of 30.5 and 18.3 cm (diagonal across the corners) were used to detect neutrons. Plastic scintillators and lead absorbers in front of the detectors were used to reject charged particles. Pulse shape discrimination technique gave a complete neutron/gamma separation down to 3 MeV. Proton registration was made with an array of sixteen $4 \cdot 4 \cdot 10$ cm^3 CsI detectors placed 60 cm from the target. Identification down to the (absorbtion) threshold of 8 MeV was possible by pulse shape discrimination.

The hexagonal neutron detectors were placed 3.5 m behind "holes" in the CsI array. Such a configuration requires corrections for false nn and np correlations due to cross-talk and scattering in the CsI array in addition to standard efficiency corrections for liquid scintillators. The efficiency correction, calculated from[8] is introduced for neutrons both in singles- and correlation yields. The frequency of false 2n events from (n, n') and (p, n) scattering in the CsI detectors, which has been

calculated analytically earlier[9], was now measured directly with the CsI array removed. This measurement confirms the calculations which give about 5% false 2n events with a shift towards larger q values. This correction is introduced in the nn data but neglected for np correlations[10].

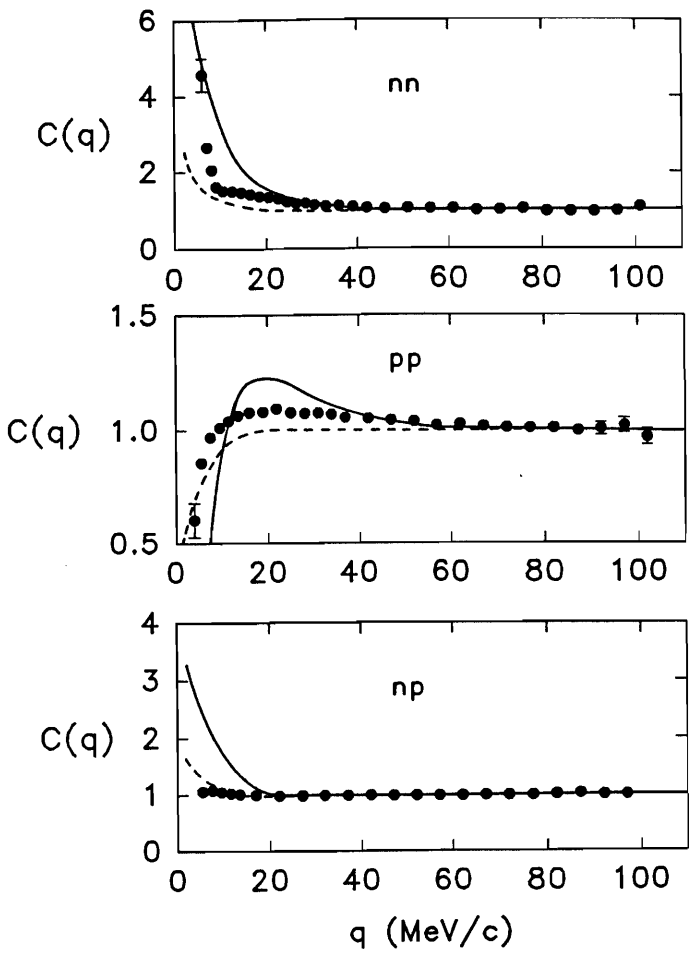
The cross-talk, calculated from the simulation program of ref.[11], gives a contribution of false 2n events of 10%. The amount of cross-talk varies drastically with the energy of the incident neutron because of the delicate combination of scattering kinematics and geometry. The simulations are well confirmed by a direct measurement with 14 MeV neutrons[12]. A complete energy dependent cross-talk distribution has been calculated (see fig. 2b) for nn (and np) correlations but they are not introduced into the data shown in fig. 1. More details about the detectors and their performance can be found in refs. [10,13,14].

In fig. 1 we present the correlation functions for nn-, pp- and np pairs measured with all CsI detectors and all hexagons + two neighbouring cylindrical liquid scintillators in the horisontal plane. The average emission angle is 45°. All neutrons above 3 MeV and all protons above 8 MeV are included. The experimental correlation function is taken to be $C(q) = N_c(\vec{p_1}, \vec{p_2})/N_{nc}(\vec{p_1}, \vec{p_2})$ where the denominator is constructed by event mixing[9,10]. Qualitatively the pp- and nn correlation functions behave as expected from a combination of the two-particle wave function symmetrization and final state effects. The pp correlation peak is slightly broader than the one for ^{20}Ne + ^{59}Co in ref[9] but this depends on the angular resolution which was better in [9] due to the use of MWPC planes. The effects from the limited angular resolution is introduced in the calculated correlation functions. Our pp function agrees well with those reported in [15] for Xe + Al,Sn reactions with apparent source radii of 5 - 6 fm.

Realistic calculations based on a pure time dependent evaporative emission process[16] (dashed curves) have been introduced. A true compound reaction is assumed where all initially available energy excites the total system. The disagreement is striking in the low q region. The pp and nn correlation peaks are both underpredicted. More realistic reaction dynamics and pre-equilibrium emission processes based on Boltzmann-Uehling-Uhlenbeck (BUU)[17,18] as well as BUU + evaporation calculations have therefore been performed. The solid curves in fig. 1 are the results from BUU calculations up to a time of 150 fm/c without additional evaporation. These results are generated from that part of the test-particle distribution which is moving away from the residual nucleus and has positive energy at a nucleon density $< 0.1\rho_o$.

In this approach the phase-space evolution is deep-inelastic like for peripheral

collisions and fusion like for central collisions. For the phase-space distribution of protons the Coulomb interaction (after 150 fm/c) with the residual nuclei has been added in a classical approximation. The potential describing the mean field is based on a soft equation of state, $V(\rho) = -356\rho/\rho_o + 303(\rho/\rho_o)^{7/6}$ [MeV] and free nucleon-nucleon cross-sections are used.



1. Experimental nn-, pp- and np correlation functions at 45° from 30A MeV Ar + Au collisions compared to calculated functions from a pure evaporative approach (dashed curves) and a BUU approach (solid curves).

Obviously the BUU pre-equilibrium component can account for the peaks in the pp- and nn correlation functions. Adding evaporation from residue(s) with initial properties given by the BUU results at 150 fm/c, suppresses the nn- (and np) correlation peak(s) while the pp peak is almost unaffected. Probably the evaporation

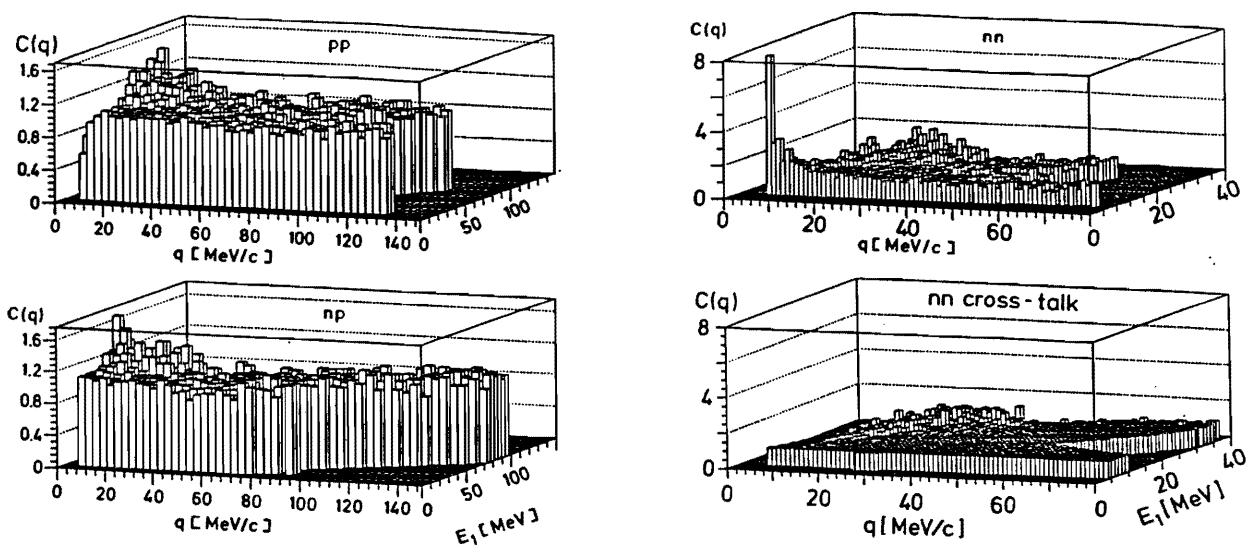
of neutrons is overestimated in this approach and furthermore it should be stressed that all "charged test particles" are tied up in protons in the BUU calculation. The exact weight for BUU and evaporative emission cannot be introduced at this stage since there is too large uncertainty in the extraction of parameters like mass, charge and excitation energy of the residual system(s). The results depend also on BUU input parameters such as the potential and in-medium cross-sections as well as on the time for switching to evaporation.

The very weak q dependence of the np correlation function cannot be reproduced by any standard calculation. In fig. 2 the nucleon energy dependence of the correlation functions is shown. We choose the energy of one particle (the neutron in the np case) as the second variable but the results are qualitatively the same if the sum of the two energies or the smallest energy is chosen instead. The np correlation peak is significant only for large neutron (or proton) energies. The destruction of the correlation peak when pairs of low energy nucleons are included may be due to the general difference between pre-equilibrium and equilibrium processes. However, it is even more probable that the expected final state correlation is destroyed by the Coulomb field acting on the proton[19]. If one adds artificially a radial "Coulomb momentum vector" to one of the neutrons in the experimental nn pairs also that correlation peak is destroyed but no realistic choice of Coulomb momenta can reproduce the flat np function in detail.

Fig. 2 tells us that also the pp correlation peak is increasing with increasing proton energy. The absence of the same phenomenon in the nn case is artificial since the smallest angle between the neutron detectors makes the very low q region unavailable. It is of course of great importance for nn- and np interferometry experiments to populate this region. This can only be achieved by a combination of a very low energy threshold and small relative angles. For nn pairs this enhances however the cross-talk[10]. In the lower right hand part of fig. 2 we show the calculated cross-talk correlation function normalized to the same number of coincidences as in the nn correlation figure. The calculations are based on a modified version of the simulation program described in[11]. The main contribution to the cross-talk comes from the C(n,n')C and C(n,n')3α reactions. The similarity between the cross-talk correlation function and the structure of the experimental correlation function outside the true final-state peak is striking.

The np system has two spin states with S = 0 and 1 with the bound deuteron always in the S = 1 state. The singlett state gives a positive q = 0 peak and the triplett state an anti-correlation[20,19]. A normal mixture between the spin states leads to a correlation peak with half the height of the nn peak[19]. Since the experimental peak is much lower one could imagine that the spin state population

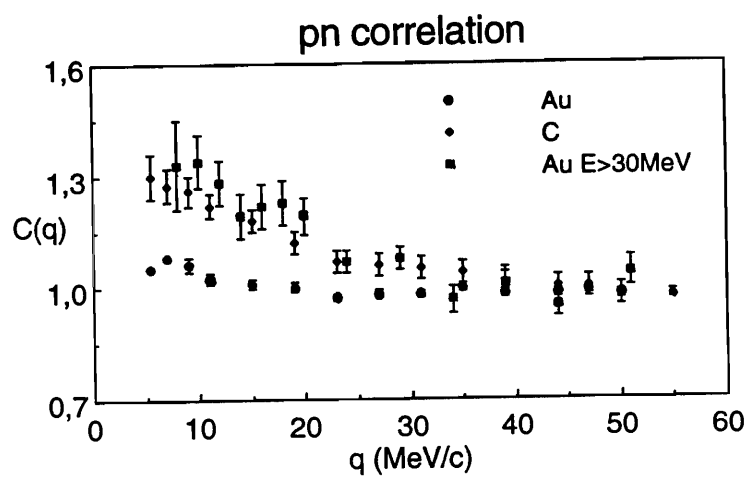
is abnormal. The deuteron emission cross-section is large - it has been measured to $\sim$ 200 mb - compared to the unbound np cross-section which makes any conclusions about a shift in the d/np ratio difficult. It has been suggested[20] that the angular momentum of the emitting system may couple to the np spin, thereby increasing the effective spin.



2. Experimental nn-, pp- and np correlation functions at 45° from Ar + Au collisions at 30A MeV. The energy axis gives the energy of one of the two particles in a pair (see text). The lower right figure shows the result of a cross-talk simulation.

As mentioned before, also the mean Coulomb field acting on the proton can cause a decrease of the correlation peak[19]. In fig. 3 we show the difference between the unbiased correlation function and the one obtained with a strong selection of high energy nucleons (both nucleons have E > 30 MeV). Again we observe a

peak for small q values but it does not reach the value (C $\sim$ 2-3) expected from the calculated correlation functions (fig. 1). Finally, we show also in fig. 3 preliminary data for the correlation function from ^{40}Ar + ^{12}C reactions[7]. It appears as if a smaller system, with a weaker Coulomb field, also exhibits an enhanced correlation peak.



3. Experimental np correlation functions for Ar + Au reactions (this exp.) and Ar + C reactions[7] as well as for a high energy (E_p > 30 MeV and E_n > 30 MeV) sample in the Ar + Au reaction.

The pp- and nn correlation functions do agree qualitatively - but not in detail - with those expected from a combination of symmetry effects in the relative wave function and final state effects as they appear in BUU + evaporation calculations. The possibilities to obtain conclusive information about the space-time development of the emission sources depend strongly on how well one can measure an unbiased correlation function for very small q values. The weak np correlation, which is enhanced when a high energy threshold is introduced or when a reaction involving smaller nuclei is considered, indicates the importance of the mean Coulomb field.

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