Two-proton correlation functions for equilibrium and non-equilibrium emission

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Two-proton correlation functions are compared for equilibrium and non-equilibrium emission processes investigated, respectively, in "reverse kinematics" for the reactions $^{129}Xe+^{27}Al$ and $^{129}Xe+^{122}Sn$ at $E/A=31$ MeV and in "forward kinematics" for the reaction $^{14}N+^{197}Au$ at $E/A=75$ MeV. Observed differences in the shapes of the correlation functions are understood in terms of the different time scales for equilibrium and preequilibrium emission. Transverse and longitudinal correlation functions are very similar.

Two protons, emitted at small relative momenta from an excited nuclear system, carry information about the space-time characteristics of the emitting source [1-11]. The shape of the two-proton correlation function reflects the interplay of the short-range attractive nuclear interaction, the Pauli exclusion principle, and the long-range repulsive Coulomb interaction between the two emitted protons. The short-range nuclear interaction is dominated by the attractive singlet S-wave nuclear interaction which leads to a pronounced maximum in the two-proton correlation function at relative momentum $q \approx 20$ MeV/c, when the average distance upon emission is of the order of 10 fm or less [1]. The long-range Coulomb interaction and the Pauli exclusion principle give rise to a minimum at $q=0$. Some directional information can be provided by antisymmetrization effects [1,7,8].

The average distance between two coincident protons upon emission depends on the spatial dimension, d, and the average lifetime, τ, of the emitting system; it is of the order of $d+\bar{v}\tau$, where $\bar{v}$ is the average velocity of the emitted protons. For the decay of equilibrated compound nuclei with temperatures below 5 MeV, estimated lifetimes are larger than several hundred fm/c [12]. As a consequence, the average distance between emitted particles is much larger than the size of the emitting nucleus and the effects of the Coulomb interaction and the Pauli principle should dominate. On the other hand, preequilibrium light particle emission in intermediate energy heavy ion collisions is calculated to proceed

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on much shorter time scales [13,14] and average particle separations may reflect the spatial dimension of the emitting system rather than the emission rate. Here, the nuclear interaction should be prominent.

In this Letter, we report a comparative study of two-proton correlation functions measured for preequilibrium and equilibrium emission processes. When light projectiles impinge on heavy target nuclei, preequilibrium emission is strongly enhanced at small angles, whereas equilibrium emission dominates at backward angles, see e.g. refs. [5,10,11]. Preequilibrium emission was studied in "forward kinematics" for the reaction $^{14}N+^{197}Au$ at $E/A=75$ MeV. Equilibrium emission was studied at a lower energy, $E/A=31$ MeV, in "reverse kinematics" for the reaction $^{129}Xe+^{27}Al$ and for the nearly-symmetric system $^{129}Xe+^{122}Sn$.

The experiments were performed with beams from the K1200 cyclotron from the National Superconducting Cyclotron Laboratory at Michigan State University. We used ^{27}Al, ^{122}Sn, and ^{197}Au targets with areal densities of 5.6, 5.3, and 15.9 mg/cm^2, respectively. Light particles were detected with two ΔE-E detector arrays consisting of 300-400 μm thick silicon ΔE detectors and 10 cm long CsI(Tl) or NaI(Tl) E detectors. An array consisting of 37 Si-CsI(Tl) telescopes [15] was centered at the polar and azimuthal angles of $\theta=25°$ and $\phi=0°$; each of its detectors had a solid angle of $\Delta\Omega=0.37$ msr and a nearest neighbor spacing of $\Delta\theta=2.6°$. Another array consisting of 13 Si-NaI(Tl) telescopes was centered at $\theta=25°$ and $\phi=90°$; each of its detectors had a solid angle of $\Delta\Omega=0.5$ msr and a nearest neighbor spacing of $\Delta\theta=4.4°$. Coincidence and downscaled singles data were taken simultaneously. Energy calibrations were accurate to better than 2%. Typical detector energy resolutions were of the order of 2% and 1% for protons of 40 MeV and 100 MeV, respectively. All data were corrected for random coincidences.

The two-particle correlation function, $R(q)$, is defined in terms of the coincidence yield, $Y_{12}(\boldsymbol{p}_1,\boldsymbol{p}_2)$, and the single particle yields, $Y_1(\boldsymbol{p}_1)$ and $Y_2(\boldsymbol{p}_2)$:

$$\sum Y_{12}(\boldsymbol{p}_1,\boldsymbol{p}_2)=C_{12}[1+R(q)]\sum Y_1(\boldsymbol{p}_1)\,Y_2(\boldsymbol{p}_2). \qquad (1)$$

Here, $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ are the laboratory momenta of particles 1 and 2, and q is the relative momentum of the particle pair. For each experimental gating condition, the sums on both sides of eq. (1) are extended over all energy and detector combinations corresponding to the given bins of q. The normalization constant, C_{12}, is determined by the requirement that $R(q)=0$ for large relative momenta.

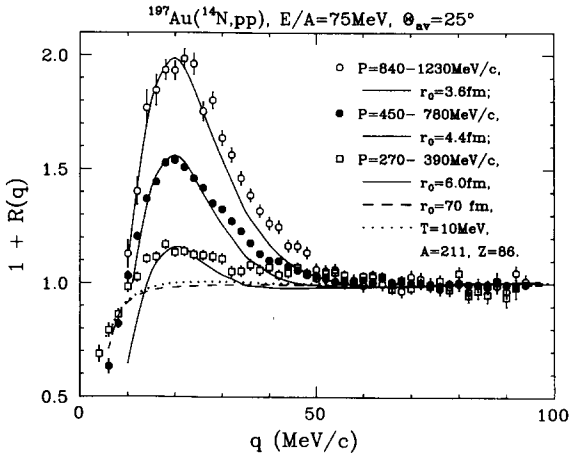

Fig. 1. Two-proton correlation functions measured for the $^{14}N+^{197}Au$ reaction at $E/A=75$ MeV for the indicated gates on the total momentum, P, of the two-proton pair. The solid and dashed curves show predictions for gaussian sources of negligible lifetime and the dotted curve shows calculations for an evaporative source with parameters indicated on the figure.

Two-proton correlation functions measured for the $^{14}N+^{197}Au$ reaction are shown in fig. 1. A strong dependence on the total laboratory momentum, P, of the coincident proton pair is measured, consistent with previous observations [2-6,8]. The solid curves show theoretical correlation functions predicted for sources of gaussian density, $\rho(r)\propto\exp(-r^2/r_0^2)$, and negligible lifetime, providing an upper limit for the size of the emitting system. For the high total momentum gates, rapid nonequilibrium processes dominate and the neglect of temporal effects may be justifiable [8]. The lowest total momentum gate selects protons of low energy, $E\approx 10$-20 MeV, for which contributions from equilibrated target residues may be important. For this gate, the shape of the minimum at $q\approx 0$ can only be reproduced by short-lived sources of unphysically large dimensions (dashed curve) or by long-lived evaporative sources discussed below (dotted curve).

Two-proton correlation functions measured for the $^{129}Xe+^{27}Al$ and $^{129}Xe+^{122}Sn$ reactions at $E/A=31$ MeV are shown in fig. 2. They exhibit a minimum

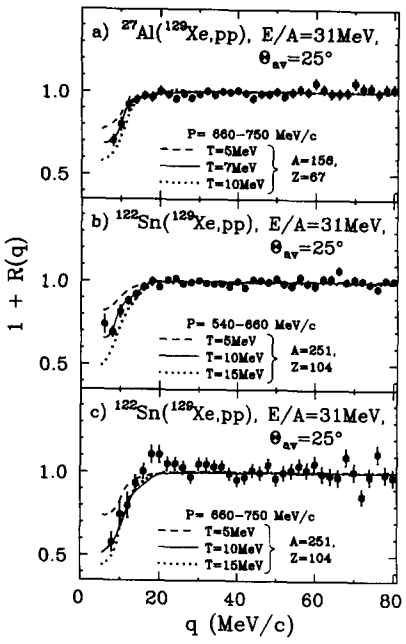

Fig. 2. Two-proton correlation functions measured for the ^{129}Xe+^{27}Al (part a) and ^{129}Xe+^{122}Sn (parts b, c) reactions at $E/A = 31$ MeV for the indicated gates on the total momentum, P, of the two-proton pair. The curves represent calculations for evaporative sources with parameters indicated on the figure.

at $q \approx 0$, but no maximum at $q \approx 20$ MeV/c. Correlation functions of similar shape were reported for equilibrium emission in the ^{16}O+^{27}Al reaction at $E/A = 8.75$ MeV [9] and for the ^{40}Ar+Ag and ^{16}O+^{197}Au reactions at $E/A = 44$ and 94 MeV [10,11], respectively. The data shown in fig. 2 correspond to proton energies slightly above the compound nucleus Coulomb barrier and are expected to be dominated by emission from long-lived equilibrated composite nuclei formed in incomplete fusion reactions [15].

Correlation functions for particle evaporation from long-lived compound nuclei can be calculated by using the Wigner-function formalism of ref. [7]. We have performed such calculations for the simple evaporative model of ref. [12]. In this model, the level density is approximated by that of an ideal Fermi gas at normal nuclear density. The results, averaged over the appropriate momentum bins and folded with the resolution of the experimental apparatus, are shown by the dotted curve in fig. 1 and the solid, dashed, and dotted curves in fig. 2. The parameters used in these calculations (initial mass, A, charge, Z, and temperature, T, of the decaying nucleus) are indicated in the figures. Since emission rates should depend more strongly on the temperature [12] than on the mass and charge number of the emitting nucleus, we used the compound nucleus values for A and Z, but treated T as a free parameter. For complete fusion of ^{129}Xe+^{27}Al and ^{129}Xe+^{122}Sn, temperatures of 8.2 and 10.3 MeV, respectively, are calculated if one assumes the level density of an ideal Fermi gas of normal nuclear matter density. The more common relation, $T^2 = (8\ \text{MeV}) \times E^*/A$, gives temperature values of 5.8 and 7.3 MeV. However, the equilibrated emitting systems should have somewhat lower temperatures [5,16-18] since some energy is carried away by preequilibrium emission. For simplicity, we assumed isotropic emission in the rest frame of the compound nucleus. Similar results are obtained by assuming isotropic emission in rest frames co-moving with heavy reaction residues formed in incomplete fusion reactions. Good agreement between calculations and the data for the Xe-induced reactions is obtained with initial temperatures of about 7-10 MeV. For the ^{14}N+^{197}Au reaction, the assumption of emission from an equilibrated nucleus is less justified; the reproduction of the data in the low momentum gate is somewhat worse.

The dependence of the two-particle correlation function on the angle, $\Psi = \cos^{-1}(\boldsymbol{P} \cdot \boldsymbol{q}/Pq)$, between the relative and total momentum vectors of the two-proton pair can provide clues on the source lifetime and shape [1,7,8]. Qualitatively, emission from a long-lived system will resemble a source elongated in the longitudinal direction [7,8]. Because of the reduced Pauli anticorrelation in this direction, the longitudinal correlation function ($\Psi \approx 0°$ or 180°) of a long-lived source may be enhanced compared to the transverse correlation function ($\Psi \approx 90°$), unless the average particle separations become so large that sensitivity to antisymmetrization effects is lost. Very similar longitudinal and transverse correlation functions were measured [8], at $\theta \approx 30°$, for the ^{32}S+Ag reaction at $E/A = 22.3$ MeV. These results ruled out long lifetime effects for the emission of preequilibrium light particles. Our data for the ^{14}N+^{197}Au reaction are qualitatively consistent with those of ref. [8]. More recently, differences between longitudinal and transverse correlation functions of the order of

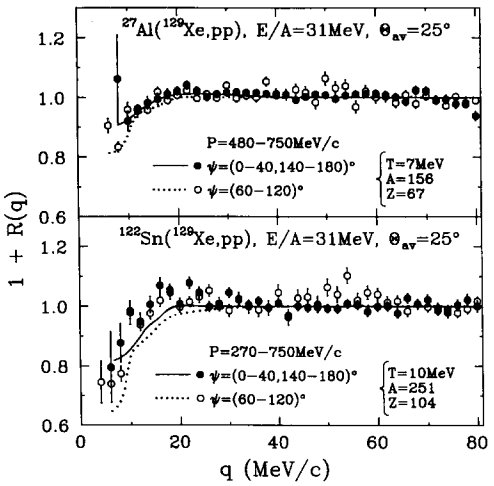

Fig. 3. Longitudinal and transverse two-proton correlation functions measured for the ^{129}Xe + ^{27}Al (top) and ^{129}Xe + ^{122}Sn (bottom) reactions at $E/A = 31$ MeV for the indicated gates on the total momentum, P, of the two-proton pair. The curves represent calculations for evaporative sources with parameters indicated on the figure.

20% were reported [11] for back-angle emission in the Ar + Ag reaction at $E/A = 44$ MeV which is dominated by emission from equilibrated residues formed in incomplete fusion reactions. We have evaluated longitudinal and transverse correlation functions for the Xe-induced reactions, by applying cuts of Ψ_l = 0°–40° or 140°–180° and Ψ_t = 60°–120°. In fig. 3, our data are shown by the open and solid points; calculations with the indicated parameters are shown by the solid and dotted curves. (In order to increase the statistical accuracy, the momentum gates have been made wider than in fig. 2; the inclusion of additional near- and sub-barrier emission leads to slightly worse agreement between experimental and calculated correlation functions.) No statistically significant difference between longitudinal and transverse correlation functions is measured. This result is in accordance with the calculations for which the predicted differences are below the statistical sensitivity of the experiment. The curves in fig. 3 represent calculations for sources co-moving with the compound nucleus; similar results are obtained for sources co-moving with heavy residues formed in incomplete fusion reactions.

In summary, we have measured two-proton correlation functions for equilibrium and preequilibrium emission processes. Correlation functions measured for preequilibrium emission exhibit a pronounced maximum at relative momenta $q \approx 20$ MeV/c and a minimum at $q \approx 0$ MeV/c which are, respectively, caused by the attractive singlet S-wave interaction between the two emitted protons and the combined effects of the Coulomb repulsion and the Pauli principle; the time scales are sufficiently short that memory of the size of the emitting system is retained. Correlation functions observed for evaporative processes do not exhibit a maximum at $q \approx 20$ MeV/c, but only the minimum at $q \approx 0$ MeV/c; large emission time intervals lead to large separations between emitted particles and a loss of memory of the size of the emitting nucleus. Two-proton correlation functions measured in kinematic regions dominated by equilibrium emission could be quantitatively reproduced by statistical model calculations based on the Weisskopf formula. For the present system, no significant differences between longitudinal and transverse correlation functions were found, in agreement with statistical model calculations which predict them to be below the sensitivity of our measurement.

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References

[1] S.E. Koonin, Phys. Lett. B 70 (1977) 43.
[2] W.G. Lynch et al., Phys. Rev. Lett. 51 (1983) 1850.
[3] Z. Chen et al., Phys. Lett. B 186 (1987) 280.
[4] Z. Chen et al., Phys. Rev. C 36 (1987) 2297.
[5] J. Pochodzalla et al., Phys. Rev. C 35 (1987) 1695.
[6] J. Pochodzalla et al., Phys. Lett. B 174 (1986) 36.
[7] S. Pratt and M.B. Tsang, Phys. Rev. C 36 (1987) 2390.
[8] T.C. Awes et al., Phys. Rev. Lett. 61 (1988) 2665.
[9] P.A. DeYoung et al., Phys. Rev. C 39 (1989) 128.

[10] J. Québert et al., Proc. Symp. on Nuclear dynamics and nuclear disassembly (Dallas, April 1989), ed. J.B. Natowitz (World Scientific, Singapore, 1989) p. 337.
[11] D. Ardouin et al., University of Nantes Internal Report LPN-89-02.
[12] W.A. Friedman and W.G. Lynch, Phys. Rev. C 28 (1983) 16.
[13] J. Aichelin and G. Bertsch, Phys. Rev. C 31 (1985) 1730.
[14] W. Cassing, Z. Phys. A 329 (1988) 471.
[15] W.G. Gong et al., Nucl. Instrum. Methods A 268 (1988) 190.
[16] R. Wada et al., Phys. Rev. C 39 (1989) 497.
[17] D.X. Jiang et al., Nucl. Phys. A 503 (1989) 560.
[18] H.M. Xu et al., Phys. Rev. C 40 (1989) 186.