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Comment on the Neutron-Proton Interferometry.

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Abstract. – We argue that in multifragmentation reactions taking place at intermediate energies, the neutron-proton correlation measurements are not suitable for the source radius determination. The relatively strong push which the proton experiences in the Coulomb field of the emitting source destroys the expected correlation at low momenta.

Measurements of correlation between identical particles such as pions, protons or neutrons provide valuable information about the space-time extension of the emitting source (for a recent review on this subject we refer to ref. [1]). In principle, the correlation of non-identical particles such as of neutrons and protons could also be used to get information on the size of the source. First n-p correlation data obtained in the collision of ^{16}O on ^{27}Al at 215 MeV incident energy have been reported in ref. [2]. The correlation pattern for the n-p pairs found in this low-energy reaction was not strongly marked. These early findings seem to be in line with recent measurements at higher beam energies [3] displayed in fig. 1. For the $^{40}Ar + {}^{12}C$ collision at 30 MeV per nucleon no pronounced correlation effects are observed for relative momenta of the n-p pairs as small as 4 MeV/c. But it is important to realize that in the same experiment n-n correlations show a rather pronounced correlation pattern pointing to a source radius being comparable with that of the projectile nucleus.

The magnitude of the n-p or n-n correlation due to the final-state nucleon-nucleon interaction should be similar. In fact, as we will quantify below, for relative momenta $q = 0$ the n-p correlation may be expected to be about half the n-n correlation. Given that, how can one reconcile the experimentally observed strong n-n correlation with such a small n-p correlation? In this note we want to give a qualitative interpretation of the observation. We will show that the lack of a pronounced n-p correlation can be attributed to the relatively strong push which the proton experiences in the Coulomb field of an emitting source.

First we derive expressions for the correlation functions that apply to n-n pairs and would also apply to n-p pairs if the Coulomb interaction of the proton with the emitting residue were

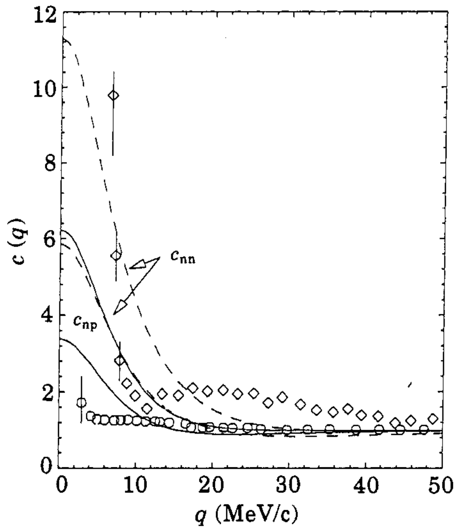

Fig. 1. – n-p (○) and n-n (◇) correlation functions (solid and dashed lines, respectively) for an emitter of radius of 4 and 6 fm. The experimental data for the reaction $^{40}Ar + ^{12}C$ at 30 MeV per nucleon at $\Theta_L =$ $= 45°$ are of ref. [3].

absent. The correlation functions can be written in the form

$$c_{nn}(q) = \frac{1}{4}c_0^1(q) + \frac{3}{4}c_1^1(q) \tag{1}$$

and

$$c_{np}(q) = \frac{1}{8}(c_0^0(q) + c_0^1(q)) + \frac{3}{8}(c_1^0(q) + c_1^1(q)), \tag{2}$$

where the upper and lower indices refer to the isospin T and spin S of the two-particle system, respectively, and q is the relative momentum. By neglecting, for the sake of simplification, the possible time dependence of the emitting source, the correlation functions for the spin-isospin channels can be expressed in terms of the two-nucleon wave function as

$$c_S^T(q) = \int d^3r D(r) |\Psi_S^T(\mathbf{r})|^2 . \tag{3}$$

Here $D(r)$ is the nucleon source normalized to unity. Since the source extension is expected to be large compared to the nucleon-nucleon interaction range and for low momenta the wave functions are expected to be different from the free ones only for relative $l = 0$ partial waves, the correlation functions for the different spin-isospin channels can be expressed in the form

$$c_1^1(q), \; c_0^0(q) \simeq 1 - \frac{2\pi}{q}\int dr D(r)\, r\sin(2qr) \tag{4}$$

and

$$c_0^1(q), \; c_1^0(q) \simeq 1 + \frac{2\pi}{q}\int dr D(r) \cdot$$

$$\cdot (r\sin(2qr) + 8\sin(qr)\,\mathrm{Re}\{\exp[iqr]f_{s,t}(q)\} + 4q|f_{s,t}(q)|^2), \tag{5}$$

respectively.

The scattering amplitude $f_{s,t}(q)$ can well be further approximated within the effective range theory as

$$f_{s,t}(q) = \frac{-a_{s,t}}{1 - \frac{1}{2} r_{s,t} a_{s,t} q^2 + i a_{s,t} q} . \tag{6}$$

With the scattering length and effective range in the singlet channel $a_s = -23.7\,\text{fm}$, $r_s = 2.7\,\text{fm}$, and, in the triplet channel, $a_t = 5.4\,\text{fm}$, $r_t = 1.7\,\text{fm}$, we obtain correlation functions quantitatively close to those when solving the Schrödinger equation for a Yamaguchi or Reid potential to generate the wave functions.

Taking a Gaussian nucleon distribution for the emitting source, the integrals in (3) can be performed analytically (see also [4, 5]), but, in view of the approximations carried out so far, the use of an approximate expression agreeing with the exact one up to a few percent is warranted:

$$c_{nn}(q) \simeq 1 + \frac{1}{2} c_s(q) - \frac{1}{2} \exp[-4R_0^2 q^2] \tag{7}$$

and

$$c_{np}(q) \simeq 1 + \frac{1}{4} c_s(q) + \frac{3}{4} c_t(q), \tag{8}$$

where

$$c_{s,t}(q) \approx \left[\frac{2}{\sqrt{\pi}} \frac{\frac{1}{2} r_{s,t} a_{s,t}^2 q^2 - a_{s,t}}{R_0} + \frac{1}{2} \left(\frac{a_{s,t}}{R_0} \right)^2 \exp[-4R_0^2 q^2] \right] \cdot \frac{1}{\left(1 - \frac{1}{2} r_{s,t} a_{s,t} q^2\right)^2 + a_{s,t}^2 q^2} . \tag{9}$$

Both the n-p and n-n correlation functions are dominated by the singlet $S = 0$, $T = 1$ interaction. For small momenta one has

$$c_{np} \approx 1 + \frac{1}{8} \left(\frac{a_s}{R_0} \right)^2 \tag{10}$$

indicating that in the absence of Coulomb effects the n-p correlations should be about half the n-n correlations. For illustration, in fig. 1 we show the n-n and n-p correlation functions for emitters of radius $R_0 = 4$, $6\,\text{fm}$ together with the experimental values of the reaction $^{40}Ar + {}^{12}C$ at 30 MeV per nucleon [3]. One sees that the predicted n-p correlation function is in a severe disagreement with the experimental results, whereas the strong correlation in the n-n correlation is reasonably well reproduced. The experimental trend shown in fig. 1 has recently been confirmed for the collision of Ar on Au at 30 MeV per nucleon indicent energy [6]. For this heavier system the n-n correlations are again well pronounced, while n-p do not appear for relative momenta as low as 2 MeV/c.

To get a clue on the failure of the theoretical description for the n-p correlation, let us now estimate the effect of the Coulomb interaction on the proton in the n-p pair. The proton is accelerated and gains an energy of

$$V_C \approx \frac{Ze^2}{r_0 A^{1/3}} \approx 6\,\text{MeV} \tag{11}$$

in leaving the residue. For the estimate of the energy we took for charge and mass number $Z = 20$ and $A = 40$, respectively, adequately to the experimental situation [3]. If no residue is left, but the entire system is vaporized, the energy gain is roughly halved. The proton gains an additional momentum with respect to the neutron of the order

$$\Delta p_c \approx \frac{V_C}{v}, \tag{12}$$

where v is the velocity of the proton with respect to the residual nucleus. For an estimate we take for the proton velocity $v \approx 0.2c$ which is somewhat less than the Fermi velocity of the nucleons, and would correspond to thermally emitted protons if the source has a temperature of about 10 MeV. This gives a momentum shift of

$$\Delta p_c \approx 30\,\mathrm{MeV}/c. \tag{13}$$

Thus, the momentum shift Δp_c due to Coulomb repulsion is at least of the range within which the n-p correlation function displayed in fig. 1 is different from zero and exhibits the maximum of the correlation. Consequently, according to our reasoning there should not become apparent a noticeable correlation for the n-p channel if the emitting source has a charge number $Z \geqslant 20$. The lowering of the n-p correlation due to Coulomb distortion becomes even more drastic the more charged the emitting source is. New results for collisions of Ar on Au at 30 MeV·A beam energy confirm this trend [3]. Given the fact that the disappearance of the n-p correlation is due to the Coulomb push experienced by the proton, one should be tempted to study experimental n-p correlations by subtracting an overall Coulomb contribution.

Any rigorous and simultaneous treatment of the interaction of the proton with the disassembling source and the n-p interaction implies at least the treatment of an involved 3-body calculation. Such calculations would permit us to discuss the above results on a more quantitative level, but are expected not to imply drastic changes of the results due to the relative narrowness of the momenta which give rise to the correlation function at low q. For the calculation of the p-p correlation one had, in principle, to deal with the same problem. However, there the Coulomb repulsion within the pair is of decisive importance giving rise to anticorrelation. The interaction of the protons with the source can be neglected to some extent, because both particles experience the same repulsion.

In summary, from our simple estimate it follows that the n-p correlations due to final-state interactions are strongly distorted by the Coulomb repulsion of the proton by the emitting source. As a net effect a very moderate correlation pattern, if any, will appear.

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