news and views

Pion interferometry of nuclear collisions

from Miklos Gyulassy

THE measurement of the space-time dimensions of nuclear interaction regions formed during high energy (~1 GeV per nucleon) nuclear collisions obviously calls for rather novel techniques. That interaction region (which we call the nuclear fireball) may be roughly cigar-shaped with longitudinal and transverse dimensions ranging between 10^{-12} and 10^{-13} cm and expanding with relativistic speeds on a time scale of 10^{-23} to 10^{-22} s. In that tiny, short-lived fireball, nuclear matter may be compressed to very high densities (~10^{15} gm cm^{-3}) and heated to enormous temperatures (~10^{12} K).

The physics of nuclear systems under such extreme conditions is now the subject of a new branch of nuclear science known as relativistic nuclear collisions. Recent developments in this area have been reviewed by Goldhaber and Heckman (*A. Rev. Nucl. Part. Sci.* **28**, 161; 1978). One of the most exciting new developments has been the application of pion interferometry to deduce the space-time geometry of that nuclear fireball. The principles behind pion interferometry and the first experimental results are discussed below.

The basic idea goes back to Hanbury-Brown and Twiss (*Nature* **178**, 1046; 1956), who first used the technique of second order intensity interferometry to deduce stellar radii. They made a remarkable observation for the chaotic, incoherent light emitted by stars. While the average intensity (photon count) measured by two detectors A and B was the same, $\langle I_A \rangle = \langle I_B \rangle$, and independent of the separation R_{AB} between the detectors, the average coincidence rate, $\langle I_A I_B \rangle$, did depend on R_{AB}. For large separations $\langle I_A I_B \rangle \approx \langle I_A \rangle \langle I_B \rangle = \langle I_A \rangle^2$, but for small separations, $\langle I_A I_B \rangle > \langle I_A \rangle^2$. From the dependence of $\langle I_A I_B \rangle$ on R_{AB}, Hanbury-Brown and Twiss were able to measure stellar radii.

The reason for this variation of the coincidence rate as a function of R_{AB} is now well known and found in any modern quantum optics textbook. It originates from Bose-Einstein statistics required for integral spin particles such as photons. It is the interference between the two parts of the symmetrised wave-functions, $1/\sqrt{2}\{\psi_1(x)\psi_2(y)+\psi_1(y)\psi_2(x)\}$ describing two identical bosons that leads to the intensity interference. Physically, the enhanced correlation at small R_{AB} follows from the tendency of bosons to congregate in the same state.

Not long after the discovery of the HBT effect in astrophysics, it was rediscovered in high-energy physics in measuring correlations between identical pions. In high-energy physics it is called the GGLP effect (*Phys. Rev.* **120**, 300; 1960). Pions ($\pi^-\pi^-$) are also bosons and are thus subject to the same symmetrisation requirement as are photons. Consequently, intensity interference must also occur for chaotic pion fields. For pions, intensity interferometry involves the comparison of the coincidence rate of identical pions with momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ to the random rate of observing pions with $\mathbf{k}_1$ and $\mathbf{k}_2$. Bose-Einstein statistics lead to an enhancement of the coincidence rate over the random rate for small momentum differences. The correlation function, defined as the ratio of the coincidence to random rate, is thus larger than unity for small $|\mathbf{k}_1-\mathbf{k}_2|$. According to a theoretical analysis by Kopylov and Podgoretski (*Sov. J. Nucl. Phys.* **18**, 336; 1974), the dependence of the correlation function on $\mathbf{k}_1-\mathbf{k}_2$ in fact measures the space-time Fourier transform of the pion source density. The relation between the measured pion correlation function and the source density obtained by Kopylov has been the basis of a great many studies of the space-time dimensions of hadronic interaction regions (see for example Enzell *et al. Phys. Rev. Lett.* **38**, 873; 1977).

Most recently the pion correlation data from high-energy nuclear collisions were analysed by a University of California, Riverside group headed by R. T. Poe. The reaction studied was $Ar + Pb_3O_4 \rightarrow \pi^-\pi^- + X$ using an Ar beam with 1.8 GeV per nucleon kinetic energy (Fung *et al. Phys. Rev. Lett.* **41**, 1592; 1978). In such reactions often more than 100 charged particles (p,π^+,π^-) are observed with negative pion multiplicities up to 15. These are the remnants of the violent explosion of the nuclear fireball. Pion interferometry has given us the first glimpse of the dimension and lifetime of that fireball before its explosion. The group reported that the average radius, R_0, and the lifetime, τ_0, of the fireball were $R_0 = 3.3 \pm 0.9 \times 10^{-13}$ cm and $\tau_0 = 5 \pm (?) \times 10^{-24}$ s.

Although the statistics are as yet too few to determine the longitudinal and transverse dimensions of the fireball separately, the measured R_0 agrees well with our expectations. However, most important, this experiment demonstrated the feasibility of pion interferometry in nuclear collisions. The next generation of experiments with the Bevalac at the Lawrence Berkeley Laboratory are expected to increase the statistics greatly. We will then be able to resolve much more clearly the geometry of these fireballs.

The discussion up to now has been concerned with intensity interferometry when applied to chaotic boson fields. As recently emphasised by Fowler and Weiner (*Phys. Lett.* **70B**, 201; 1977) the intensity interference pattern also depends on the degree of coherence of that boson field. Laser fields, for example, exhibit no intensity interference. The effect of possible coherence on pion interferometry is a topic of current theoretical investigation.

A final comment that must be made is that final state interactions must also be considered in connection with future work on pion interferometry. Unlike photons, pions can interact with each other and the remnants of the exploding fireball. The effects of final state interactions (especially the long-range Coulomb forces) must be unfolded from the measured correlation data before accurate geometrical and dynamical information can be deduced from those correlations. Such studies are also now underway. □

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