HANBURY BROWN-TWISS INTERFEROMETRY IN SUBATOMIC PARTICLES

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Introduction

Many different experiments utilizing collisions have been developed to study nuclei and elementary particles. For example, Rutherford scattering involves scattering of alpha particles by the nucleus in order to learn about the charge distribution of the nucleus. This experiment takes advantage of the Coulomb interaction and the nonzero charge of the alpha particle. In a similar fashion, neutrons are also used to study the mass distribution of atomic nuclei. In the case of neutron scattering, there is no Coulomb force since the neutron possesses no charge. Rather, neutron scattering depends on the strong force. Colliders such as SLAC (Stanford Linear Accelerator Center) and CERN's LHC (Large Hadron Collider), have used another type of scattering called deep inelastic scattering, in which high energy electrons are fired at stationary target protons. This method was instrumental in particle physics for obtaining evidence for the existence of quarks. Aside from scattering experiments, another method used to study the properties of atomic nuclei and elementary particles is Hanbury Brown-Twiss intensity interferometry.

Intensity interferometry was originally developed by Robert Hanbury Brown and Richard Twiss in the mid 1950s in the field of radio and optical astronomy. It is used to measure the apparent angular diameter of a distant star or radio source [4]. A time later, the method became known as Hanbury Brown-Twiss (HBT) interferometry and was extended to the study nuclear and particle collisions. Hanbury Brown-Twiss interferometers rely on the correlations or anti-correlations of fluctuations in the intensities of a beam of particles incident on two separate detectors.

There are several significant differences between intensity interferometry used in astronomy and in particle physics. The main one is that in astronomy, the correlation gives information about the apparent size of an object in momentum space as a function of the distance between the two detectors. In particle physics the correlation gives information about how the reaction region of collisions evolves in space-time as a function of the momentum difference between two particles [7]. The sources studied in astronomy are generally considered static on the timescale in which observation occurs whereas the geometry and dynamics of sources created in high energy collisions evolve on a very short timescale. Additionally in astronomy, the particles studied are photons whereas in particle physics, the particles studied are typically pairs of pions, kaons or nucleons. Historically, the Hanbury Brown-Twiss effect has been primarily studied with pions though somewhat more recently it has also been studied with kaons and protons [9].

What follows is a brief explanation of the theory underlying the basic concepts of HBT interferometry, a basic description of the experimental method, a short summary of some significant experimental results along with a comparison between bosons and fermions and a discussion on potential implications of the experiments.

Theory

The theory presented here primarily follows the description given by G.Baym in his 1998 paper [1]. For a more thorough explanation, see reference [1]. We want to find a two particle correlation function for pion pairs from a reaction region, or a localized source of particles. We define $\langle n_{\vec{p}} \rangle$ as the average number particles of momentum $\vec{p}$ detected in a single event, and $\delta n_{\vec{p}}$ is the deviation from the mean of the number of particles detected. Then the total number of particles detected is

$$n_{\vec{p}} = \langle n_{\vec{p}} \rangle + \delta n_{\vec{p}}.$$

Consider now the average number of times two particles of momenta $\vec{p}_1$ and $\vec{p}_2$ are detected.

$$\begin{aligned}
\langle n_{\vec{p}_1} n_{\vec{p}_2} \rangle &= \langle ((\langle n_{\vec{p}_1} \rangle + \delta n_{\vec{p}_1}) (\langle n_{\vec{p}_2} \rangle + \delta n_{\vec{p}_2}) \rangle \\
&= \langle n_{\vec{p}_1} \rangle \langle n_{\vec{p}_2} \rangle + \langle n_{\vec{p}_1} \rangle \langle \delta n_{\vec{p}_2} \rangle + \langle n_{\vec{p}_2} \rangle \langle \delta n_{\vec{p}_1} \rangle + \langle \delta n_{\vec{p}_1} \delta n_{\vec{p}_2} \rangle \\
&= \langle n_{\vec{p}_1} \rangle \langle n_{\vec{p}_2} \rangle + \langle \delta n_{\vec{p}_1} \delta n_{\vec{p}_2} \rangle
\end{aligned}$$

The cross terms vanish as by definition, $\langle \delta n_{\vec{p}_i} \rangle = 0$

The last line can be rewritten as

$$\frac{\langle n_{\vec{p}_1} n_{\vec{p}_2} \rangle}{\langle n_{\vec{p}_1} \rangle \langle n_{\vec{p}_1} \rangle} = 1 + \frac{\langle \delta n_{\vec{p}_1} \delta n_{\vec{p}_1} \rangle}{\langle n_{\vec{p}_1} \rangle \langle n_{\vec{p}_1} \rangle}$$

where in general, the first term is defined as the the two particle correlation function.

The correlation that is measured in HBT interferometry is

$$C(q) = \frac{\langle n_{\vec{p}_1} n_{\vec{p}_2} \rangle}{\langle n_{\vec{p}_1} \rangle \langle n_{\vec{p}_2} \rangle}$$

where $\vec{q} = \vec{p}_1 - \vec{p}_2$ is the momentum difference between detected particles, $n_{\vec{p}}$ is the number of particles with momentum $\vec{p}$ measured in a single event, and $\langle \cdots \rangle$ denotes a time average [1].

To achieve a better normalization, the numerator and denominator of the correlation function are often averaged separately over a range of center of mass momenta $\vec{P} = \vec{p}_1 + \vec{p}_2$. Letting $\{\cdots\}$ denote this average, the correlation function is

$$C(q) = \frac{\{\langle n_{\vec{p}_1} n_{\vec{p}_2} \rangle\}}{\{\langle n_{\vec{p}_1} \rangle \langle n_{\vec{p}_2} \rangle\}}.$$

An issue that we need to consider is why HBT interferometry works. HBT interferometry relies on the Hanbury Brown-Twiss (HBT) effect which is the tendency for particle pairs to be more correlated when the relative momentum transfer q is small [3]. The HBT effect is generally attributed to the dual wave-particle nature of the beam. It involves multiparticle correlations and anti-correlations that are sensitive to the wave mechanics of particle pairs. However, in general the effects of quantum mechanics are considered to be relevant only during the time in which the particle is localized to the reaction region. Once the particles leave the reaction region, they can be viewed as "little bullets on classical trajectories" [1].

Quantum mechanically the HBT effect arises as a consequence of ordinary boson exchange. This effect is present for all pairs of identical bosons (i.e. pions and kaons produced in high energy collisions), including photons used in intensity interferometry in astronomy [1].

Experiment

The first successful experiment to detect the HBT effect from particle collisions was done by G. Goldhaber in 1960. The experiment measured the angular correlations of pions produced in $p\bar{p}$ collisions. This experiment and its results will be discussed in the results section.

In this section and the next, I will focus primarily on pion interferometry, though the general concepts are still valid for interferometry involving other types of elementary particles. Generally, the experimental setup for HBT interferometry involves nuclear collisions which form a pion producing region that is often modeled with a Gauss distribution [3]. The most effective way to detect particles of any given momentum is to enclose the reaction region within a 4π detector. This allows detection of the momenta of particles within a full solid angle of 4π.

For pion interferometry with relativistic nuclear collisions, the incident beam often consists of high energy ^{40}Ar and the targets are often made of BaI_2 or Pb_3O_4 disks with thickness of ~ 0.3 cm. This allows pions with a very low energy (≥ 10 MeV) to be detected [5]. Additionally, the target atoms have a large cross section which increases the probability of collision and pion pair production.

Collision results in the production of pion pairs. In the above mentioned classical picture the particle, in this case a pion, travels along a classical trajectory. After the collision the pion eventually traverses the detector, depositing some energy. The detector is pixelated so as to provide a measurement of the relative angle between the pion and the incident beam. The pion then continues on its trajectory and penetrates a region with a magnetic field. The magnetic field causes the trajectory to bend and as the particle is tracked, this allows us to obtain a measurment of the magnitude of the momentum. These measurements were first made using photogrpahic emulsions [1]. Because viewing the particle track requires that the particle has a nonzero charge, the π^0 particle is not directly studied in HBT interferometry (regardless, the π^0 has a very short lifetime $\sim 10^{-16}$ and can decay into gamma rays which can initiate a small shower which can be detected and used to measure the momentum). In HBT experiments, the pairs studied are π^+ or π^-. With the direction and magnitude, the momentum of the pion can be calculated to within an uncertainty of $\Delta\vec{p}$. The uncertainty arises because a particle of average momentum $\vec{p}$ can be detected in a range $\Delta\vec{p}$ around $\vec{p}$. With this information for the number of detected pions per collision, the correlation between pion pairs can be calculated.

Results

It has been found experimentally that correlation between pions is higher when the transfer of momentum is smaller. This is qualitatively consistent with theoretical predictions. However, quantitatively the correlation should equal 2 for a perfectly chaotic source when the momentum difference is small. Experimentally, the correlation reaches a maximum of $\sim 1.5-1.6$ for pion pairs produced from collisions of ^{40}Ar with BaI_2 and Pb_3O_4 [5]. This suggests that there is some underlying physics that reduces the correlation function at small momentum differences.

One potential reason for the discrepancy is that the derived correlation function does not account for the effect of Coulomb interactions on the final state particle momenta [6]. This is not negligible since the pions that are studied have charge and therefore they interact with each other as well as with the surrounding system [2].

Discrepancies between theory and experiment were also noticed earlier in the 1960s when G. Goldhaber noticed while investigating the production of pion pairs from $p\bar{p}$ annihilation that experimental observations of the angular distribution of the pion differed from the predictions of the Fermi statistical model. Here the differences may be due to multiparticle symmetrization contributions, or Bose-Einstein symmetrization, to the two particle correlation [10]. Most hadrons, including pions, are emitted in the final stage of a heavy ion collision. In the intermediate stage before they are emitted, there are other complicated processes that occur, such as the exchange of gluons between quarks. The two particle correlation function is used in attempts to determine the geometry of the emitting source based on the production of particle pairs only in the final stage. However, the geometry of pair production is highly dependent on all stages in a collision. This can be better accounted for by considering Bose-Einstein symmetrization and multiparticle correlations, which are not generally accounted for in HBT interferometry experiments such as the one done by Goldhaber.

Thus far, though I have not discussed the HBT effect for fermions, it is worth briefly outlining its differences from the effect for bosons. The behavior of particles with regard to the HBT effect should differ depending on whether bosons or fermions are being considered. The results, both theoretical and experimental, given above for pions are generally true for other bosons as well. At low momentum, bosons tend to show what is called bunching, meaning that they tend to see a higher correlation or an enhancement of the HBT signal (correlation theoretically approaches 2). This is attributable to the symmetric nature of the wave function for two identical particles. At higher momentum differences, which corresponds to the case of statistically independent particles, the particles become uncorrelated and the correlation tends towards 1. Fermions experience the exact opposite effect, called anti-bunching. At low momentum, the HBT signal is quenched which corresponds to the particles being anti-correlated and the correlation approaching 0. Like bosons, as the momentum difference increases, the particles tend to behave as statistically independent particles

[8]. These distinctions between bosons and fermions have recently been confirmed experimentally by T. Jeltes in 2007.

Potential Implications

Though there are many effects such as the Coulomb interaction, Bose-Einstein effects, or multiple scattering effects which introduce uncertainty into the measurements of the HBT effect and HBT interferometry, the basic underlying physics has many potential applications.

HBT interferometry can be applied to many other systems in addition to the ones discussed here. This is evident by the history of intensity interferometry and the fact that it was initially developed by Hanbury Brown and Twiss to measure the apparent angular size of astronomical radio sources. Since then, it has been applied to systems which exist on scales that are many orders of magnitude smaller. HBT interferometry can be applied to many other systems in addition to the ones discussed here. For example, recently, HBT correlation studies have been done in atomic systems on bosonic ^{20}Ne atoms that were ultracold but not yet Bose-Einstein condensed. In this particular study, it has been found that the correlation is inversely related to the temperature of the beam [11].

Additionally there remain many aspects of the HBT effect that are still not well understood both experimentally and theoretically. For example, it is still unclear how exactly the two particle correlation function depends on factors such as the impact parameter of the collision and the resonance decays of the particles. There is still experimental research and theoretical advancements which still remain to be done which could provide new insight into the field of particle interferometry.

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