Bunching-Antibunching of Quantum Particles
From Astronomy to AMO

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Science’s 10 Most Beautiful Physics Experiments

Robert P. Crease, a member of the philosophy department at the State University of New York at Stony Brook and the historian at Brookhaven National Laboratory, recently asked physicists to nominate the most beautiful experiment of all time. Based on the paper of George Johnson in The New York Times we list below 10 winners of this polling and accompany the short explanations of the physical experiments.

1. Double-slit electron diffraction

The French physicist Louis de Broglie proposed in 1924 that electrons and other discrete bits of matter, which conceived only as material particles, also have wave properties such as wavelength and frequency. Later (1927) electrons was experimentally established by C.J. Davission and L.H. Germer in New York and by G.P. Thomson.

To explain the idea, to others and themselves, physicists often used a thought experiment, in which Young’s double-slit experiment was repeated with a beam of electrons instead of light. Obeying the laws of quantum mechanics, the stream of particles would be scattered in all directions, and the smaller streams would interfere with each other, leaving the same kind of light- and dark-striped pattern. Particles would act like waves. According to an accompanying article in Physics World, by the magazine’s editor in chief, it was not until 1961 that someone (Claus Jönsson of Tübingen) carried out the experiment in the real world.

2. Galileo’s experiment on falling objects

In the late 1500’s, everyone knew that heavy objects fall faster than lighter ones. After all, Aristotle had said so. But a young scholar still held such sway was a sign of how far science had declined during the dark ages.

Galileo Galilei, who held a chair in mathematics at the University of Pisa, was impudent enough to question the ancient story. It has become part of the folklore of science: he is reputed to have dropped two different weights from the tower of Pisa, showing that they landed at the same time. His challenges to Aristotle may have cost Galileo his job, but he had a vision of taking nature, not human authority, as the final arbiter in matters of science.
1 Young's double-slit experiment applied to the interference of single electrons
2 Galileo's experiment on falling bodies (1600s)
3 Millikan's oil-drop experiment (1910s)
4 Newton's decomposition of sunlight with a prism (1665-1666)
5 Young's light-interference experiment (1801)
6 Cavendish's torsion-bar experiment (1798)
7 Eratosthenes' measurement of the Earth's circumference (3rd century BC)
8 Galileo's experiments with rolling balls down inclined planes (1600s)
9 Rutherford's discovery of the nucleus (1911)
10 Foucault's pendulum (1851)

Others experiments that were cited included:
Archimedes' experiment on hydrostatics
Roemer's observations of the speed of light
Joule's paddle-wheel heat experiments
Reynolds's pipe flow experiment
Mach & Salcher's acoustic shock wave
Michelson-Morley measurement of the null effect of the ether
Röntgen's detection of Maxwell's displacement current
Oersted's discovery of electromagnetism
The Braggs' X-ray diffraction of salt crystals
Eddington's measurement of the bending of starlight
Stern-Gerlach demonstration of space quantization
Schrödinger's cat thought experiment
Trinity test of nuclear chain reaction
Wu et al.'s measurement of parity violation
Goldhaber's study of neutrino helicity
Feynman dipping an O-ring in water
HBT Interferometry
instead of double-slits use two detectors

Hanbury Brown and Twiss,

Measurements of the angular diameter of Sirius
"The most common objection to our work was that the time of arrival of one photon at a detector cannot conceivable be correlated with that of another because individual photons are emitted at random times and must therefore arrive at random times. If our system was really going to work, we would have to imagine photons hanging about waiting for each other in space!"...R. Hanbury Brown [1]

Ignorance is sometimes a bliss in science:R. Hanbury Brown
Quantum World

Am I an X-ray photon...? Or a radio photon? Or visible?

Oh hell...! Why worry about all that again...? I'm not even sure if I'm a wave or a particle!

Feynman: No one understands QM
"Particles, particles, particles."
There are two types of particles in nature. Fermions and bosons.

Fermions have half units of spin, and tend to shy away from each other, like people who always stay in single rooms at the fermion motel.

Bosons have zero or integer units of spin, and like to be with each other, like people who stay in shared dormitories at the boson inn.

Anyons.... Almost 30 years ago researchers proposed a third category, "anyons," where a limited number of particles could inhabit a single state. No one has observed this property directly, but many researchers believed that the strange state of electrons observed in the 1990s in the so-called fractional quantum Hall (FQH) effect qualifies as an anyon.
Bunching-Antibunching of Quantum Particles

Simultaneous Detection: Bosons, Fermions & Tennis Balls

(1) Particles at both detectors come from source 1
    Amplitude equal to $A_1$.

(2) Particles at both detectors come from source 2
    Amplitude equal to $A_2$.

(3) Particle at detector 1 comes from source 1 and at detector 2 comes from source 2
    Amplitude equal to $A_3$.

(4) Particle at detector 2 comes from source 1 and at detector 2 comes from source 1
    Amplitude equal to $A_4$.

Classically, all paths are distinguishable and total probability of simultaneous detector is the sum of the 4 amplitude squares.

However, if particles are bosons or fermions, the last two processes are indistinguishable.

$I = (A_1)^2 + (A_2)^2 + (A_3 \pm A_4)^2$ where $\pm$ respectively refers to bosons and fermions.

Special case, $A_1 = A_2 = A_3 = A_4 = A$

$P = 4(A)^2$ for classical particles

$P = 6(A)^2$ for bosons particles

$P = 2(A)^2$ for fermions particles


expt was done at Tubingen Germany, same place where the double-slit with electrons was done in 1961
HBT applications

- **Particle physics** .. size of heavy nuclie that radiate pions
- **Quantum optics** ... testing foundation of Quantum physics
- **Condensed matter**...expt obervation of e/3 charge
- **Atomic Physics**.......Somewhat unexpectedly, the HBT effect has found a new career at the ultracold end of the energy scale, where it has turned out to be an exquisite tool for physics of quantum many body systems.
Ultra-cold atoms

- Room temperature
  - Water freezes
  - Dry ice
- N₂ condensation 77 K
- He condensation 4 K
- Absolute Zero

Temperature Scale:
- Kelvin
- Celsius

- 300 K: 27~300 m/s
- 250 K: -23°C
- 200 K: -73°C
- 150 K: -123°C
- 100 K: -173°C
- 50 K: -223°C
- 0 K: -273°C

In 1995 thousands of atoms were cooled to 0.000000001 K.

Velocity of only few cm/s
In a Bose Einstein Condensate there is a macroscopic number of atoms in the ground state.

In 1995 teams in Colorado and Massachusetts achieved BEC in super-cold gas. This feat earned those scientists the 2001 Nobel Prize in physics.

S. Bose, 1924
A. Einstein, 1925
E. Cornell
C. Wieman
W. Ketterle

Light
Atoms
Using Rb and Na atoms

In 2002 around 40 labs around the world produced atomic condensates!!!
Schools are composed of many fish of the same species moving in more or less harmonious patterns throughout the oceans. A very prevalent behavior, schooling is exhibited by almost 80 percent of the more than 20,000 known fish species during some phase of their life cycle. Many of the world's fishing industries rely on this behavior pattern to increase their catch size, especially for species such as cod, tuna, mackerel, and menhaden.
Neural atoms in the periodic table are bosons or fermions

**80% of atoms in periodic table are bosons**;
New Frontier: what can we do with cold atoms

- better clocks

- Resolve mysteries of the universe: laws of physics are still not understood

- cold atoms provide very attractive systems to work with in the Lab as they can be manipulated by lasers: optical crystals

- Systems are ideal for studies of interference phenomena and atom optics & can be used as a diagnostic for complex behavior

- Quantum Information & Quantum Computing
Bunching with He4 & antibunching with He3

Jeltes et al, Nature 2007
HBT & Many Body Quantum Physics
What is measured in cold atom experiments

Cloud is imaged (single shot image)

pixels of CCD camera act as detectors & sample the atoms (100,000 detectors instead of two)
The atoms, having flown out with the random speeds of a thermal distribution, display a Gaussian density profile & fluctuations look like regular noise.

\[ \Delta n = n(x) - \langle n(x) \rangle \]

\[ \langle \Delta n(x+d/2) \Delta n(x-d/2) \rangle \]

(*called noise correlations*)
Free fermion antibunching in a degenerate atomic Fermi gas released from an optical lattice

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Noise in a quantum system is fundamentally governed by the statistics and the many-body state of the underlying particles. The correlated noise observed for bosonic particles (for example, photons or bosonic neutral atoms) can be explained within a classical field description with fluctuating phases; however, the anticorrelations ('antibunching') observed in the detection of fermionic particles have no classical analogue. Observations of such fermionic antibunching are scarce and have been confined to electrons and neutrons. Here we report the direct observation of antibunching of neutral fermionic atoms. By analysing the atomic shot noise in a set of standard absorption images of a gas of fermionic $^{40}$K atoms released from an optical lattice, we find reduced correlations for distances related to the original spacing of the trapped atoms.
HBT (noise spectroscopy)
Bragg Diffraction that encodes quantum statistics & Much More...

studying interacting many body systems

What can we learn from HBT??
• Many body systems: weakly interacting can be described approximately by single-particle theory

• Studying strongly interacting quantum systems is one of the most challenging problems.

• Strongly interacting systems: quantum phase transitions....
Quantum phase transition from conductor to Insulator
Comparing single particle & Noise Correlations

Insulating phase
Seeing Lattice in Dark!
Noise Correlations peak at onset to Insulating (Mott) transition
\[ \hat{H} = -\frac{J}{2} \sum_{j=1}^{N} (1 + \gamma) \sigma_j^x \sigma_{j+1}^x + (1 - \gamma) \sigma_j^y \sigma_{j+1}^y + h \sigma_j^z, \]

**Magnetic Transition**

EPL, 2009: Florian, Ana Maria Rey, Indubala Satija and Charles, clark
Studying strongly Interacting Bosons
Hard Core Bosons

Turning Bosons into Fermions
- the Tonks-Girardeau Gas -

Model for Strongly Repulsive Bosons

“Almost” like Spin-1/2 system
HBT: Comparing HCB, Spin & Fermions in a periodic lattice

HCB

spin-1/2

fermions
Do HCB show any signature of fermionization
Bunching to Antibunching Transition
Figure 6. For fixed $\lambda/J = 1$ and $U/J = 20$, we plot the visibility of the central (dotted-dashed line) and superlattice induced (dashed lines) peaks as the filling factor varies. The solid and dotted lines are the corresponding HCB curves.
Period-4 lattice
Bunching-Antibunching & Missing Peak mystery !!!!

Fermions do not show missing peaks:
missing peaks only in the interacting case:
Is it signalling some important effect ???? MAY BE

Recall historically: extra peaks led to discovery of electron spin: Missing peak, what information it encodes about strongly interacting particle ?? Is there something really important
disordered (Incommensurate) Lattice
Bunching-Antibunching & missing peaks
Disorder induced metal-insulator transition

Derivative of noise correlation w.r.t. strength of disorder peaks at the transition to insulating phase: this derivative diverges in HCB.
In last 4-5 years, studying quantum noise was one of my area of research. I have few papers... Let me acknowledge my collaborators and found many interesting aspects of quantum noise: that is quantum noise provides quite an illuminating description of many phenomena.
Summary

• The story of HBT effect is remarkable in its origin, in its importance and in its impact. There is something very revealing, beautiful and inspiring about the effect. When we see its applications, we are drawn to its roots: historical journey that begins with the work of Dirac, Heisenberg, Pauli and Fermi and others...... experimental demonstration of bunching antibunching with photons, electrons and then with neural atoms that are bosons or fermions is an important milestone......................

• physicists looking for new phenomena, or new exotic states of matters may find quantum noise an important asset

• Beyond HBT: It turns out that the distribution of shot noise can provide a wealth of knowledge about various quantum correlations of the many body system of without a perfect phase. In other words, hidden in noise are all the richness and complexities of many body system.
CONCLUSIONS  (The Tragedy of Hamlet,  by Shakespeare):

There are more thing in heaven and earth,
Horatio, than are dreamt of in your philosophy.
The quantum interpretation of bunching relies on the constructive interference between amplitudes involving two indistinguishable photons, and its additive character is intimately linked to the Bose nature of photons. By contrast, fermions should reveal an antibunching effect (a tendency to avoid each other). Antibunching of fermions is associated with destructive two-particle interference, and is related to the Pauli principle forbidding more than one identical fermion to occupy the same quantum state.
Information encoded in the Quantum Noise

Interference experiments with cold atoms are of single-shot type and do not represent the quantum measurement which requires averaging over many experimental runs. A single shot image picks a definite phase of the condensate. Therefore, absence of interference fringes in the average over many experimental runs does not mean that interference fringes are absent in a single shot.

So one may wonder what kind of information is contained in the whole distribution of interference patterns from different shot images?? The complete distribution gives average as well as deviation from the average, called the noise. It turns out that the distribution of shot noise can provide a wealth of knowledge about various quantum correlations of the many body system of BEC without a perfect phase. In other words, hidden in noise are all the richness and complexities of many body system.

Ref: Fundamental noise in matter interferometers”, AdiletImambekov, Vladimir Gritsev and Eugene Demler, 2007
Effect of Disorder
Comparing Boson & Fermion Noise Correlations in Anderson localized phase

HCB
Fermions

red (finite disorder), Blue (Analytic results for large disorder)
Large Disorder

\[ \Delta(Q[n]) \equiv \Delta_n \approx \nu \delta_{n,0} - \frac{2\nu(1-s)}{L} + \frac{(-1)^s \sin^2[\pi \nu n]}{(\pi n)^2}. \]

\[ [s=0 \text{ (hard core bosons)}, s=1 \text{ (fermions)}] \]
Scaling

Extended Phase

\[ n(0) \approx N^{1/2} \]
\[ \Delta_{00} \approx N \]

Critical Point

\[ n(0) \approx N^{1/4} \]
\[ \Delta_{00} \approx N^{1/2} \]

Localized Phase

\[ n(0) \approx N^0 \]
\[ \Delta_{00} \approx N^0 \]
Fermionization of HCB: Peak-Dip transition
Parameters:
- Densities: $10^{15}$ cm$^{-3}$
- Temperatures: Nano Kelvin
- Atom Numbers $10^6$

Ground States at $T=0$

Bose-Einstein Condensates
e.g. $^{87}$Rb

Degenerate Fermi Gases
e.g. $^{40}$K
THE PHYSICS OF HANBURY BROWN–TWISS
INTENSITY INTERFEROMETRY:
FROM STARS TO NUCLEAR COLLISIONS *

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In the 1950’s Hanbury Brown and Twiss showed that one could measure the angular sizes of astronomical radio sources and stars from correlations of signal intensities, rather than amplitudes, in independent detectors. Their subsequent correlation experiments demonstrating quantum bunching of photons in incoherent light beams were seminal in the development of quantum optics. Since that time the technique of “intensity interferometry” has become a valuable probe of high energy nuclear and particle collisions, providing information on the space-time geometry of the collision. The effect is one of the few measurements in elementary particle detection that depends on the wave mechanics of the produced particles. Here we discuss the basic physics of intensity interferometry, and its current applications in high energy nuclear physics, as well as recent applications in condensed matter and atomic physics.
Probing ultracold atoms

Time of flight images

\[ t=0 \] Turn off trapping potentials

Imaging the expanding atom cloud gives important information about the properties of the cloud at \( t=0 \): Spatial \( \rightarrow \) Momentum
• Solving the mysteries of the universe: as fundamental forces are still not understood:

• (a) Are laws of physics changing with time? Recent theories suggest that fine structure constant may be changing slowly with time and also may exhibit sparial variation. A new generation of ultraprecise clocks will help to answer this.

• (b) Time-reversal symmetry: by measuring the electric dipole moment of the atom.
Statistically induced Phase Transitions: Turning Bosons smoothly via Anyons into Fermions

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Anyons – particles carrying fractional statistics that interpolate between bosons and fermions – have been conjectured to exist in low dimensional systems. In the context of the fractional quantum Hall effect (FQHE), quasi-particles made of electrons take the role of anyons whose statistical exchange phase is fixed by the filling factor. Here we propose an experimental setup to create anyons in one-dimensional lattices with fully tuneable exchange statistics. In our setup, anyons are created by bosons with occupation-dependent hopping amplitudes, which can be realized by laser-assisted Raman tunneling. The statistical angle can thus be controlled in situ by modifying the relative phase of two Raman laser beams. This opens the fascinating possibility of smoothly transmuting bosons via anyons into fermions and of inducing a phase transition by the mere control of the particle statistics as a free parameter. In particular, we demonstrate how to induce a quantum phase transition from a superfluid into an exotic Mott-like state where the particle distribution exhibits plateaus at fractional densities.

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Usually, every particle in quantum theory is classified as either a boson – a particle happy to fraternize with any number of identical particles in a single quantum state – or a fermion, which insists on sole occupancy of its state. The exchange of two fermions leads due to the Pauli principle to a phase factor -1 in the total wavefunction, while the wavefunction of two bosons remains invariant under particle exchange. A long time ago, researchers proposed a third fundamental category of particles living in two-dimensional (2D) systems, “anyons” [1–3]. For two anyons, the wavefunction acquires a fractional phase $e^{i\theta}$ under particle exchange, giving rise to fractional statistics, with $0 < \theta < \pi$. For a few years the scenario for anyons remained restricted to the 2D world [4–6], until Haldane presented the concept of fractional statistics in arbitrary dimensions [7]. The playground for anyons in one dimension (1D) is still unexplored to a wide extent. Recently, it has been put forward to create fractional statistics in a 1D Hubbard model of fermions with correlated hopping processes [8].
HBT by calculating the Intensity-Intensity correlation where one treats Electromagnetic radiation as a classical wave.

Consider a single incident wave with freq $\omega$ on two detectors. Since the detectors are separated, say the second detector gets a signal delayed by a phase $\phi$,

\[
I_1 = E^2 \sin^2(\omega t) \\
I_2 = E^2 \sin^2(\omega t + \phi) \\
< I_1 I_2 > = E^4/4 + E^4/8 \cos(2\phi) \\
< \Delta I_1 \Delta I_2 > = E^4/8 \cos(2\phi)
\]

where $\Delta I = I - < I >$. 
New Frontier: what can we do with cold atoms

- Better clocks
- Resolve mysteries of the universe: laws of physics are still not understood
- Cold atoms provide very attractive systems to work with in the Lab as they can be manipulated by lasers: optical crystals
- Systems are ideal for studies of interference phenomena and atom optics & can be used as a diagnostic for complex behavior
- Quantum Information & Quantum Computing
In 1949, Robert Hanbury Brown undertook a challenging task of measuring the sizes of the radio wave sources that were discovered right after the development of the radar technology. It was realized that the standard amplitude interferometry could not be used as the two antennas whose signals were to be added have to be thousands of kilometers apart.
Quantum theory of HBT experiments

Glauber, Quantum Optics and Electronics (1965)

For bosons

\[ A = A_1 + A_2 \]

For fermions

\[ A = A_1 - A_2 \]

HBT experiments with matter

- Experiments with 4He, 3He: Westbrook et al., Nature (2007)
Trapping Atoms in Light Field - Optical Dipole Potentials

Energy of a dipole in an electric field:

$$U_{dip} = -\vec{d} \cdot \vec{E}$$

An electric field induces a dipole moment:

$$\vec{d} = \alpha \vec{E}$$

$$U_{dip} \propto -\alpha(\omega) I(\vec{r})$$