# BOSE-EINSTEIN CONDENSATES AS UNIVERSAL QUANTUM MATTER

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*S. N. Bose gave a new identity to the quanta of light, introduced into physics by Planck and Einstein, and derived Planck's formula for the radiation spectrum. Chance events led to Einstein's insightful use of Bose's result to build a quantum theory of atomic gases, with the remarkable prediction of a new type of condensation without interactions. Though the spectacular phenomena of superfluidity and superconductivity were identified as the consequences of Bose-Einstein Condensation, the phenomenon in its near pure form, as foresaw by Einstein, was observed 70 years later in atomic gases. The quest for atomic gas BEC was behind much of the developments of laser cooling and trapping of atoms. Since then, the atomic gas BEC has grown into a major research theme and versatile research tool all over the world. I outline the development that made BEC of laser cooled atoms the promised 'Swiss army knife' of laboratory physics, with mentions of some of the examples and applications. My involvement in this field of research at 'home and the world' is briefly reviewed.*

## *A Derivation that was a Quantum Leap*

Foundations of physics are often unsettled. Physicists have to make postulates, assumptions and various approximations to reach where intuitions and empirical data converge. In this process, it is not unusual that concepts with some mutual tension from previous theories and experience are mixed with new insights, as and when needed. Satyendra Nath Bose was looking at one such important instance in the course of his teaching in the university, when he decided that the derivation that changed and revolutionized physics, of the Planck's law of the spectral distribution of the black body radiation, was conceptually deficient and unsatisfactory. Planck's quanta was transformed to particles of light by Einstein and the experimental evidence for their particle nature in photoelectric effect was convincing to the physics world (and to the Nobel committee). The quanta of light possessed energy $E = h\nu$ and momentum $p = h\nu/c$, where $\nu$ referred to the frequency of an underlying oscillator. Bose noticed that all previous derivations of the Planck's law treated the counting of quanta with a particular range of energy by treating them as standing waves in a confined space, familiar from classical electrodynamics, and not by treating them as particles. He was troubled by this inconsistency. He set out to correct that glaring conceptual flaw by calling a particle a particle. That exercise culminated in the "Indian Bose's beautiful derivation" of the Planck's radiation law, the details and history of which are discussed and documented widely.[1]

As well known, some events related to Bose's attempt to publish his derivation finally brought the paper to Einstein's desk, with a daring and confidently humble request to help in the publication after translation to German. Einstein saw the importance of dealing with light quanta as 'atoms of light', translated the paper and helped Bose in its publication.[2] Meanwhile Einstein made a characteristic conceptual quantum leap.

Planck's formula for the spectral density of radiation consists of three factors. First is the number of 'modes of radiation' with frequency $\nu$, considered as the standing waves in a containing box; this is the coefficient $8\pi\nu^2/c^3$.

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Other two are Planck's expression for the energy of a quantum, hν, and the statistical factor of average occupation (probability) $1\Big/\left(\exp\left(\frac{h\nu}{kT}\right)-1\right)$ of the state of energy $E = h\nu$. The '-1' factor in the denominator is the signature of Planck's quantum revolution. Bose's immediate achievement, in his own words, was to "deduce the coefficient in Planck's law independent of the classical electrodynamics".

What was striking in Bose's derivation was his treating the quanta of light as particles with energy $E = h\nu$. and momentum $E = h\nu/c$. There is no mention of waves of radiation. Bose's friend and classmate, Meghnath Saha had already used (in 1919) the concept of the momentum of the quanta in the astrophysical context to deduce that absorbing a 'corpuscle of light' could significantly alter the trajectory of atoms.[3] Bose assumed that the light quanta occupied 'elementary cells' of volume $h^3$ in the phase space of coordinates and momenta. The volume of the phase space with momentum between $p$ and $p + dp$, occupying spatial volume unit, would be $4\pi\ p^2dp = 4\pi h^3\ \nu^2\ d\nu\big/c^3$ . Accounting for the two polarization states one gets $8\pi h^3\nu^2 d\nu\big/c^3$ . (Apparently, Bose meant and wrote 'two states of spin directions' rather than 'polarization states', but Einstein changed it to a more conventional, though inconsistent, description). Dividing by the volume of each phase space cell, $h^3$ according to Bose, one gets the number of quantum states and thus the important coefficient in Planck's law correctly. Thus, the factor hitherto derived using classical electrodynamics and counting of standing waves in a box, Bose derived 'quantum theoretically', for the first time. This was the original and new contribution, as stressed by Bose himself, and highlighted by Einstein.[2] Bose's derivation marked an important conceptual advance. The other details of Bose's paper followed some earlier derivations, but now with the quanta occupying the cells of phase space in different ways (the indistinguishability of the quanta was already recognized in some earlier derivations).

Einstein applied the insight and inspiration gained from Bose's paper on the 'photon gas' to the quantum mechanics of a thermal atomic gas.[4] The momentum of a particle for a given energy $E$ is $p = (2mE)^{1/2}$. Following Bose's steps, Einstein got the number density of phase space cells as $2\pi V(2m)^{3/2}E^{1/2}$. He deduced that the gas of atoms followed a quantum mechanical law very similar to Planck's law for their statistical distribution, with the average number of atoms per cell as $\langle n\rangle = 1\Big/\left(\frac{\exp(E-\mu)}{kT}-1\right)$. With their number conserved, unlike photons, atoms distribute with a 'chemical potential' μ, which approaches zero at low temperature.

Einstein noticed a peculiar feature occurring at low temperature.[5] The total number of atoms is limited, at temperature T in volume V as

$$N = \alpha(2\pi mkT)^{3/2}\, V\big/h^3$$

(The numerical factor α = 2.612 is $\sum_j j^{-3/2}$ over all positive integers). Thus there is a maximum density *N/V* (or minimum temperature $T_c$), beyond which the added particles have to go to a state where their presence would not be felt!

Einstein wrote[5], "So what happens when we increase the density of the substance, N/V, at constant temperature (for example by isothermal compression)? I suggest that in this case, as you increase the overall density, an ever increasing number of molecules drop into the ground state (i.e. the first quantum state, state of no kinetic energy)...My prediction is the emergence of something very similar to what occurs when vapour is isothermally compressed beyond the saturation volume. A separation will take place; one part will condense, the rest will remain as a 'saturated ideal gas' ...When exceeding this density the surplus molecules will drop out as immobile ('condensing' without forces of attraction)."

I think that decades of intimacy with thermodynamics and statistical physics helped Einstein to see this subtle result transparently. Bose-Einstein Condensation is the most spectacular prediction from the thermal statistical distribution of gas atoms, called the Bose-Einstein distribution.

### *Bose-Einstein Condensates in the Laboratory*

The prediction from the 'most famous physicist' remained undiscussed for years, until Fritz London's calculations and identification, in 1938, of the superfluid Helium as a genuine Bose-Einstein condensation transition.[6] Despite the binding interactions in the liquid phase, the light atoms of Helium has significant zero-point energy that makes them loosely bound, almost like the atoms of a gas, a fraction of which becomes a Bose-Einstein Condensate (BEC). That superfluid Helium is a BEC was evident from its physical behaviour and the closeness of the condensation temperature to the one calculated from Einstein's theory.

The relation between superconductivity and Bose-Einstein Condensation is not straightforward because the electrons with half-integer intrinsic spin are involved. It was known that the statistical behaviour of particles with integer values for their intrinsic spin (like photons) is drastically different from those with half-integer spin. However, the mysterious fact that only the total spin of a composite entity matters for determining its quantum statistical behaviour gave clarity for the identification of superconductivity as involving the BEC of the bound 'Cooper pairs' of electrons, with total zero spin.[7]

Attempts to produce a near ideal BEC in atomic gases were pursued slowly, starting in late 1970s with Hydrogen, notably by D. Kleppner in the USA. This turned out to be extremely difficult with many technical hurdles. However, a variety of experimental techniques and insights were developed on the way to reaching low effective temperatures. The thermodynamic temperature in this case refers to the average kinetic energy in a thermalised sample of atoms, as $E_k = \frac{1}{2}mv^2 \approx kT$. Most important of these techniques was perhaps the method of evaporative cooling, to be discussed later.

An explosive development in atomic physics and in the field of atom-light interactions, which happened in a relatively short time of a decade, changed the entire scenario.[8] First was the rapid progress in the precision spectroscopy of atomic transitions using lasers.[9] The invention of the remarkably simple pump-probe saturation spectroscopy enabled identifying the transitions without Doppler broadening and tuning of the laser frequencies to these transitions with a precision of a part in $10^9$. Meanwhile, several types of new laser sources, including many semiconductor lasers, became available. Radiation pressure from photons on atoms, 'out of proportion to the sizes of the atoms' as M. N. Saha remarked, became the tool for slowing down and stopping atoms, and holding them in the diffusive viscous state, called the optical molasses. Ideas and techniques in the new field of laser cooling of atoms grew quickly, adapting from the extensive theoretical knowledge developed in the interaction of light with two level and three level atoms, especially optical pumping and coherent state manipulations. At the low kinetic energy corresponding to the temperature below a milli-Kelvin and speed of a few m/s speed, atoms can be held with very small forces, available from their interaction with magnetic fields and light. A suggestion by J. Dalibard in Paris to combine a small quadrupole magnetic field with appropriately polarized light beams to create a magneto-optical trap (MOT) to spatially confine the laser cooled slow atoms enabled much of the subsequent experimental activity. Realizing the BEC of nearly non-interacting atoms in the gas phase was one primary goal. However, other areas like precision spectroscopy, metrology, matter-wave and atomic state interferometry and detailed study of many features of atomic physics itself, flourished as well.

The cooling of gases to the low temperature required for the transition to a BEC is set by the condition of *quantum degeneracy*. The maximum density in Einstein's formula happens when a fundamental quantum cell of size of the order of de Broglie wave length contains more than one particle, or equivalently the inter-particle separation is smaller than the quantum wavelength. This amounts to slowing the atoms down to an average velocity of a few cm/s, keeping the density low enough to avoid other types of conventional condensations. The thermal de Broglie wavelength at temperature T is $\lambda_{dB} = \hbar / (2mkT)^{1/2}$. Then the degeneracy condition is approximately $n\lambda_{dB}^3 > 2$. At a gas density of about $10^{14}$ atoms/cm$^3$, the required refrigeration is to a temperature of around a micro-Kelvin.

In 1995, the first atomic gas BEC was created in a spectacular fashion by researchers from the National Institute of Standards and Technology and University of Colorado, USA, with Rubidium atoms, which have mild repulsive interactions.[10] To be fair, it was like a marathon race ran by several competent groups, and a few getting to the podium eventually, with others finishing close. This, as well as the techniques for laser cooling, were recognized as major contributions, with Nobel prizes in 1997[11] and 2001.[12] Crucial to this breakthrough was the solution to the problem of holding the atoms in a 'trap' (or a cage) at high density while progressively cooling them to the required ultra-low temperature below a micro-Kelvin. The proven technique for progressive and continuous cooling was called 'forced evaporative cooling' in a magnetic trap. The method involves two important stages. One is to trap the atoms in a three-dimensional magnetic trap. This is possible because the interaction of the magnetic field and the magnetic moment of the atom is 'attractive' for one orientation of the spin and repulsive for the other. Atoms can be spin polarized with light in the favourable orientation. The magnetic field direction changes in the trap, but if the atoms are moving slowly, their spin direction follows the direction of the field and the atoms are stable trapped, except if the atoms pass through the centre of the trap where the magnetic field is zero. Then the spin can flip and the atoms can be lost from the trap. This problem was solved by adding a small rotating magnetic field to the strong quadrupole field of two coils with opposite currents. The next step is the evaporative cooling, allowing the 'hottest' atoms with the highest energies in the trap to escape while the rest of the atoms collide and thermalise. This can be forced by selectively spin flipping atoms above a certain energy, because in a magnetic trap the Zeeman energy and the spin flip energy gap increase outwards from the trap centre. Starting with a radio-frequency field at a resonant frequency corresponding to some peripheral circle in the trap, one progressively reduces the frequency to eject the highest energy atoms, while allowing the rest to thermalise. This way, the average energy and temperature come down continuously, while the hot atoms are lost from the trap, as in the familiar cooling of liquids by evaporation.

From the early days of BEC of alkali atoms like Rubidium and Lithium, the atomic gas BEC list has now grown to span a wide range of properties in the atomic table. The list now includes $^1$H, $^4$He*, $^7$Li, $^{23}$Na, $^{39}$K, $^{41}$K, $^{40}$Ca, $^{52}$Cr, $^{85}$Rb, $^{87}$Rb, $^{84}$Sr, $^{86}$Sr, $^{88}$Sr, $^{133}$Cs, $^{164}$Dy, $^{168}$Er, and $^{174}$Yb (numbers specify the isotope mass number).

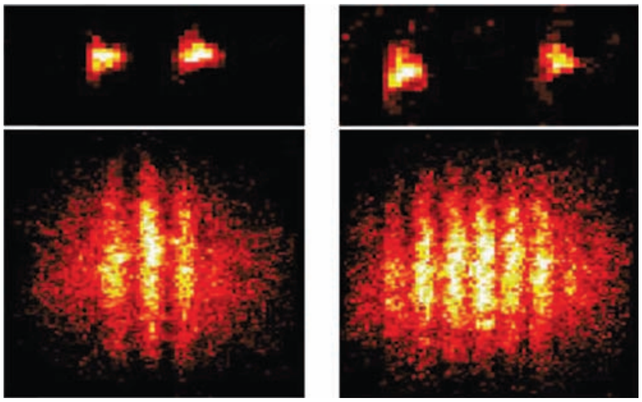

**Figure 1:** Interference of BEC ($^{87}$Rb) released from a split-source (double-well) on an 'atom chip'. The fringe spacing decreases as the seperation between the coherent sources increase, similar to the double-slit interference in optics.

All the atoms of a Bose-Einstein condensate are in the ground state, occupying the same quantum state. This is reflected in the 'wave nature' of the entire BEC, with the de Broglie wavelength corresponding to the uncertainty momentum of a single atom. This phase coherence of the matter-wave is impressively seen in the direct interference of the condensate released from two traps[11], much like the double slit interference (Figure 1).

### *BEC with Bosonic and Fermionic Atoms*

Einstein's quantum theory of mono-atomic gases assumed that all atoms behave similar to Bose's light quanta. Starting with the Pauli exclusion principle, physicists learned that fundamental particles with their spin angular momentum quantized as $\hbar/2$ (half-integer spin) behave very differently from particles that have integer spin, like Bose's photons. Formal developments completed the classification into two — the Bose-Einstein statistics to describe the collective behaviour of particles of integer spins and the Fermi- Dirac statistics to describe those of half-integer spins. The former class of particles came to be known as Bosons and the latter class, as Fermions.

All the fundamental particles that make the atom - electron, proton and neutron - are Fermions with spin $\hbar/2$. An atom is not a fundamental particle. Then how do we decide whether a given atom is a Boson or a Fermion? Most interestingly, and equally enigmatically, what matters physically is the 'external appearance', in that the total spin of the different particles together determines the spinorial nature of the composite. In fact, the phenomenon of superconductivity is a remarkable consequence of this feature. The conducting charge carriers in materials are electrons, which are Fermions. However, two electrons can pair up through a weak attractive interaction available in the material lattice, and then the pairs with the integer spin (0 or 1) behave like Bosons and condense into a free flowing BEC at low temperature. Thus, atoms come in both varieties - Bosons and Fermions. In fact, while one isotope of a species of atom, like Potassium-39 with 19 protons and 20 neutrons can behave as a Boson, another isotope Potassium-40 with one more neutron is a Fermion. Therefore, $^{39}$K can be made into a BEC, but not $^{40}$K. Another such pair is Lithium isotopes of $^7$Li and $^6$Li. The drastic difference is seen when one cools the two species in similar experiments (figure 2). The quantum pressure of Fermions that resist compression is the reason for the stability, up to a maximum density, of the compact stars like white dwarfs and neutron stars, as first discovered by S. Chandrasekhar.

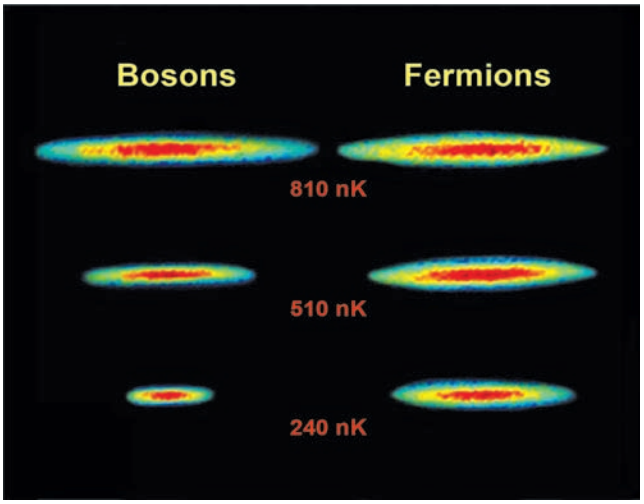

**Figure 2:** The contrasting behaviour of Bosons and Fermions at quantum degeneracy is spectacularly shown by two isotopes of ultra-cold Lithium atoms ($^7$Li and $^6$Li). Bosons condense and Fermions resist compression (from the lab of R. G. Hulet, www.atomcool.rice.edu)

The experimenters were very innovative in designing and executing experiments with Fermionic atoms. Since

Fermions in identical states obey the Pauli exclusion principle, spin-polarized cold Fermions in a magnetic trap do not collide and thermalise. Hence, evaporative cooling is not an option to cool them to quantum degeneracy. A clever way is to arrange for 'sympathetic cooling' where a evaporatively cooled Bosonic species is used to simultaneously cool the Fermions in the same trap[14]. If the Fermionic atoms are made to pair up into composite dimers first, they can subsequently become a BEC. Since this route is similar to the pairing up of two electrons to become a 'Cooper pair' that subsequently pass to the condensed phase BEC, as described by the BCS theory of superconductivity, this is refereed to as BCS-BEC route. In the case of the atoms, the strength and sign of the pair interactions are tunable with what is called the Feshbach resonance, in the presence of a magnetic field. Working with Fermionic isotopes of atoms like Lithium and Potassium enabled unprecedented studies that are inaccessible in condensed matter systems.[14]

## *BEC at Home and the World*

My involvement with Bose-Einstein Condensates has a home story as well as some prior history abroad. Fascinated with the possibilities of laser cooled atoms, especially in metrology and research in gravity and foundational issues in quantum physics, I sought to learn the techniques from the experts. At the Laboratoire Kastler Brossel (LKB) of the École Normale Supérieure, Paris, I joined a determined group, and a complicated experiment, trying to condense Helium atoms.

The Helium atoms are peculiar in that it is not the atoms in the ground states that have to be cooled. The spectral transitions in Helium suitable for laser cooling is accessible only when one of the electrons is excited, using a discharge. This excited state with the enormous energy of 19.2 eV is 'metastable', with a very long lifetime of about 8000 seconds, as long as the atoms are protected from collisions – even collisions among atoms can violently deexcite the metastable He* atoms.

It was a massive effort, led by the senior colleagues Claude Cohen Tannoudji (Nobel laureate, 1997, for developing ideas and theory of laser cooling of atoms) and Michèle Leduc, along with several of us with experience in different aspects of experimental physics. My association was intermittent, during the regular visits of several months a year. We built up an entirely new experiment with an efficient discharge source of He* atoms and Zeeman slower that slowed down metastable Helium atoms from over a km/s to below 50 m/s, suitable for trapping in the 3D MOT. A large low density MOT received and held these atoms which were subsequently transferred to a magnetic trap, after spin polarizing the atoms. Spin conservation prohibits spin-changing collisional de-excitation in spin-polarized gas. The evaporative cooling was not easy, made more difficult for monitoring by the low sensitivity of camera at these wavelengths. Finally in January 2001, simultaneously with another group led by Alain Aspect in the neighbouring Institute d'Optique[15], BEC of metastable He atoms was achieved[16], thanks to the persistence and courage of the then graduate student Franck Pereira dos Santos.

While at LKB, I started formulating a sure and reliable way of achieving an 'all-optical BEC' with the simpler Rubidium atoms ($^{87}$Rb), after a discussion with M. S. Chapman from Georgia Institute of Technology, who made a BEC in a purely optical trap, instead of in a magnetic trap. He remained the only one who managed to do so, despite several others trying the method, even years after his feat in 2001. Atoms experience a pure trapping force without any scattering and radiative force, towards the high intensity region of a focused laser beam, if the optical frequency is much lower than the transition frequencies of the atom. While the magnetic trap BEC needed holding cold atoms for over 50 seconds in the trap, optical route needed only a few seconds of evaporation. In such optical dipole traps, evaporative cooling amounted to just slowly reducing the intensity of the trapping laser beam. The novelty was tempting. It was obvious to many that the key to success was in getting a starting sample of large number of cold atoms at high density.

I designed a 10 cm long 2-dimensional MOT as the source of pre-cooled atoms to load a dense 3D MOT in another chamber with lower pressure. It took a few years to arrange the finances and a laboratory at TIFR. But, the asset any funding cannot get was ready at hand – hard working and enthusiastic graduate students. While the first student Ashok Mohapatra built and established the basic techniques, the next two - Saptarishi Chaudhuri and Sanjukta Roy - working as an untiring pair, set up the whole scheme for BEC within three years. The experiment consisted of several elements – Lasers for cooling, 2D+MOT, 3D MOT, $CO_2$ laser for the optical trap, modulators and countless optical elements around a ultra-high vacuum set up at $10^{-11}$ mbar. It involved complicated optical set up and alignment, electronics and programming of pulse sequences for automatic controls, sensitive CCD camera etc. Working with the powerful and invisible infrared beams of the $CO_2$ laser, at about 50 Watts, had to be done carefully. We innovated resources and methods for a large number of hitherto unfamiliar tasks.

Once we were ready, it was only a matter of months to see the first glimpses of the Bose-Einstein condensation.

The dipole optical trap was formed with the stable beam of a $CO_2$ laser, with reduced intensity fluctuations and pointing jitter. The tight trap of about 40 micron size was formed by crossing two focused beams and we had over $10^8$ atoms at the start of the evaporative cooling. Within about 1 s, the evaporation takes the sample to a few hundred nano Kelvin and high density exceeding $10^{14}$ atoms/cm$^3$, when the condensation happens[17]. We also did some experiments where the condensation was performed in even tighter traps formed as an optical lattice. This is a series of periodic potential wells formed in the standing waves of light, when the focussed $CO_2$ laser beam is retro-reflected symmetrically and overlapped on itself.

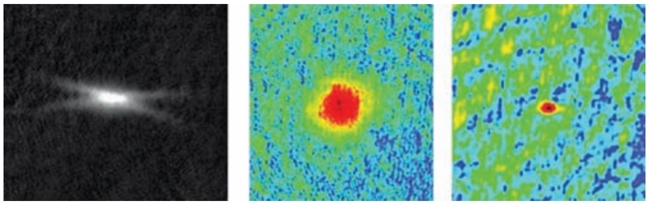

**Figure 3:** Formation of the BEC in the TIFR experiment. The frame on left shows the cold atoms held in a tight optical trap formed by two crossed $CO_2$ laser beams. Middle: Ultra-cold atoms slowly expanding in the early stages of evaporative cooling. Right: The dense BEC, when the atoms are cooled to about 200 nano-Kelvin.

The news of this first home-BEC, and one of the very few all optical BEC then, was enthusiastically carried by the Indian press in 2007, especially in Kolkata and Mumbai. The then prime minister of India, Dr. Manmohan Singh, who was also at one time in the governing council of TIFR, was very attentive of the modest yet significant development and sent individual letters of appreciation to the three researchers involved.

It was amusing that many senior theoretical physicists who showed great enthusiasm and activism about making a BEC in Bose's home country remained lukewarm and uninterested when the first Indian BEC was made by our small group at TIFR. Most physicists working on theoretical aspects here have never stepped into the laboratories were things happen. Due to this noninteracting or even mildly repulsive nature, experimenters are rarely motivated by the work of theorists here, which is an unfortunate situation.

It took another 8 years for the second BEC to be formed in an Indian laboratory, of Umakant Rapol at the IISER, Pune.[18] This was in a robust set up with a Zeeman slower as the source of the pre-cooled atoms and the BEC was formed in a quadrupole magnetic trap. This seems to be the only operational facility for BEC based experiments at present in India.

Atoms in a BEC have zero kinetic energy. But they have the quantum zero point energy. From the uncertainty principle we know that $\Delta p \approx \hbar/\Delta x$. Hence, if the condensed atoms are released from an anisotropic trap, the momentum and the rate of expansion are the largest in the direction in which the atoms are more tightly confined; then the initial anisotropy in space inverts after some expansion! The images in figure 4 show this phenomenon in our Rb BEC.

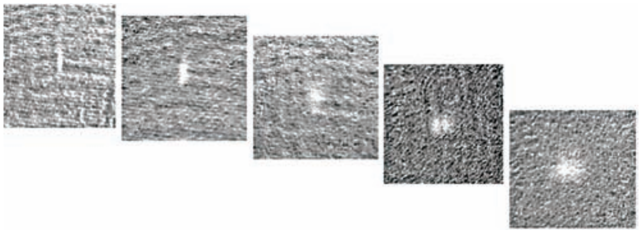

**Figure 4:** Expansion of the BEC with the quantum zero point energy of the atoms. The momentum is the largest in the direction of the tightest confinement. This is seen as the inversion of the initial anisotropy, with hardly any expansion in the vertical direction in this case.

## *BEC in Fundamental Physics and Applications*

The Bose-Einstein Condensate is a quantum phase transition, quite unlike the phase transitions we are familiar with, like steam to water, or water to ice etc. Though it involves going below a critical temperature, BEC does not involve any interactions. In fact it happens even with mildly repulsive interaction. It is a new state of matter, where the wave-particle duality manifests in a sample wide coherence. One may say that the quantum wavelength becomes larger than the typical inter-particle separation. But, the effect is more subtle; once the condensation happens, the state remains robust in spite of splitting the condensate or the expansion of the sample that increases the inter-particle separation beyond the quantum wavelength. BEC based experiments and theory have become a new culture (or cult) in physics, with a large number of researchers pursuing a still growing terrain of ideas and techniques.[19]

### *Atomic Physics*

Except for the fact that all atoms in a BEC are in identical quantum state, the lowest energy state, there is no change in the atomic properties. Many atomic species spanning a wide range of atomic properties have been condensed, enabling very focused study of electronic structure based atomic interactions. The interest in atoms like Cr and Dy is that they have very large magnetic moments and can be used to study entirely new features of atomic magnetism.

The quantum theory of BEC of weakly interacting atomic gases is described by a multi-particle Schroedinger equation which has a density dependent potentials, called the Gross-Pitaevskii equation[20]. Since the density is essentially the square of the wavefunction, $|\Psi|^2$, this is a nonlinear Schroedinger equation. Superfluidity and collective modes of oscillations, vortex generation in rotating condensates, etc. were the early studies. The enormous amount of work done in the context of atomic gases[20] is difficult to summarize. I will not attempt the impossible here.

### *Condensed Matter Physics*

The atomic BEC has contributed most to the study of simple phenomena in condensed matter physics, involving multiparticle collective effects. The relevant phenomena are transport and conductivity, superfluidity and quantum tunneling. Some initial experiments focused on elementary phenomena of vortex formation and their dynamics, by rotating and imparting angular momentum to the atomic BEC with the help of focussed light fields (tweezers). The scene changed drastically by the demonstration of a spectacular transition from a superfluid phase to an insulating phase in an optical lattice, analogous to what might happen for electron conduction in a crystal lattice. The lattice in this case was optical, periodic potential wells made by standing waves of light in 1,2 and 3 dimensions.[21] The optical lattice can be easily created, with widely tunable trapping depth and spatial period, by interfering optical beams. The transport of the atoms loaded in the lattice is then controlled by just two parameters; the mild repulsive interaction between the atoms, and inter-site tunneling or 'hoping', related to the depth of the potential wells. This allows the realization of the versatile condensed matter model Hamiltonian systems called the Bose-Hubbard model[22] and variations (there is also the equivalent for Fermionic cold atoms called the Fermi-Hubbard model). In the real condensed matter situation, electrons in the potential wells of the lattice, there is no tunability of the parameters. In optical lattices, the trap depth proportional to the light intensity is easily varied. This allows a through and nearly complete study of the model Hamiltonian in the laboratory. Since the depth of the potential well is easily tunable, one can study the whole range of phenomena as if the strength of the interaction is varied.

In the much discussed example of the phase transition from the superfluid phase to the Mott insulator, the atoms freely tunnel in the superfluid phase when the potential well is shallow; they are collectively coherent, with a common quantum phase. Hence, when the trap is released, matter wave interference results in an interference pattern. As the trap depth is increased, the system goes to the phase transition to an insulator, each atom in individual trap. Then the phase coherence is lost. Atoms released from the trap result in a fully decohered pattern. Several such phenomena, with wider domain of relevance, have been explored with BEC. Two examples of lower dimensional phenomena are the Anderson localization due to weak disorder and the Berezinskii-Kosterlitz-Thouless transition in a Bose gas in layered 2-dimensional optical traps.

### *Metrology*

One analogy that is often mentioned is between a laser and a BEC. The analogy is based on the existence of a threshold for the onset of coherence, like a single long wave, and the fact that photons are Bosons. However, a laser is not a Bose-Einstein condensate. Yet, the analogy is helpful in certain applications. A BEC of atoms which is sourced continuously or in pulses from a single source is often called a 'atom laser'.[23]

At one stage in the peak of these technological developments, BEC was projected as a unique and powerful tool for precision metrology. This was expected from the comparison between the atomic BEC and the immensely useful and universal tool of lasers. The stable wave nature aides in tremendously precise interferometry, where physical measurements are possible to within a thousandths of the de Broglie wavelength. Concurrently, physical interactions like gravity cause differential phase shift of millions of radians, between two beams separated by a few millimetres! Thus the relative precision could be better than an impressive $10^{-10}$, in a single run of the experiment. This exceeds the precision achievable in optical metrology in many cases. Laser cooled atoms were already employed in such precision metrology, since the coherence of a BEC is not an essential requirement for such measurements. Atomic interferometry can be performed with just laser cooled atoms, much like optical interferometry without lasers. BEC has certain advantages, like the ability to form a 'interference fringe' directly at the region where the matter waves overlap (fig. 1), but the added experimental difficulty is making the BEC offsets these advantages, except in special metrological situations.

In the important metrological area of atomic clocks, ultra-cold atoms in optical lattices and laser cooled ions have taken the centre stage. BEC with their collective interactions do not figure here because good atomic clocks need to isolate the atoms from even small and subtle interactions. While cold atom interferometry is now commercial technology, BEC based metrology is still confined to the physics laboratory and special situations. I do not foresee a drastic change in this situation in the near future.

### *Other Projected Applications*

Unlike the decisive technological developments that have been enabled by laser cooled atoms and ions, the technological promise of atomic gas BEC is yet to be realized. Cold atoms have revolutionized atomic clocks, interferometers for navigation and metrology, magnetometry, and improvement of metrological standards and measurement of fundamental constants. In contrast, BEC have proven promise only in some limited areas of inertial and gravitational metrology, till today. Some precision fundamental physics experiments like the test of the equivalence principle, conventionally done using instruments like torsion balances, have been attempted with BEC. The much advertised fundamental difference because of the use of the 'quantum sensor' is a naive interpretation of such tests and need not be given much importance. BEC have been very important in fundamental physics studies of condensed matter and strongly correlated matter, naturally. But I doubt they will assume a comparable stature in applications. The often repeated claim of its potential importance in quantum computing also is unlikely to be realized at a technologically useful scale.

There are some spectacular advances in the technology to produce atomic gas BEC. I mention a recent challenging experiment that produced the BEC of Rubidium atoms in low gravity, in a compact automated laboratory of size 0.5 m diameter and 2.8 m length, in space flight on board a sounding rocket.[24] In a parabolic flight with microgravity conditions lasting for about 6 minutes, an international team from Europe successfully produced the BEC on an 'atom chip' magnetic trap several times and conducted a large number of experiments, with the ultimate goal of high precision atom interferometry in space. The production rate was about $10^5$ atoms in BEC, in about 1.6 s. This experiment with many technological implications was led by Ernst Rasel, who was also the mainstay in our He* BEC experiment, two decades ago.

A critical element in producing reliable BEC in remotely handled situations, like in space, is what is called the 'atom chip', which has been popular with the cold atom community for two decades.[25] An atom chip is an integrated compact assembly of lithographed current carrying conductors on a reflecting substrate with carefully designed switchable conductor geometries for generating magnetic field configurations suitable for laser cooling and trapping. Usually pre-cooled atoms are loaded close to the surface mirrors of such chips and held in magnetic traps to do further evaporative cooling to a BEC. With careful design, such chip BEC are versatile and reliable. The technological goal is to integrate the entire experimental configuration, including some of the laser beams derived from a single laser, on a compact and portable assembly.

### *S. N. Bose and My Research*

My scientific trajectory has crossed the terrain named after S. N. Bose a few times by now, transcending the time and generations gap. First was in the Bose-Einstein condensation experiments with Helium and Rubidium.

The next was when I found that that the spin-statistics connection is the consequence of the gravitational coupling of the spin of the particles and the matter-energy of the universe, reaching to the core of the Boson-Fermion distinction. This fundamental feature in physics was revealed in the gravitational paradigm for relativistic physics, called Cosmic Relativity, which I developed.[26] The spin is the closed current of the charge of gravity, mass-energy, much like the magnetic moment in electromagnetism. Therefore, the phase changes due to the gravitational interaction of an integer spin (Boson) is decisively different from that of an half-integer spin (Fermion).

The third instance is in my exploration of the unphysical nature of the zero point energy (ZPE) of the electromagnetic vacuum in quantum optics and quantum electrodynamics. The infinite (or at least very large) number of wave modes, each carrying the ZPE $h\nu/2$, implies a very large energy density, which is in stark conflict with cosmology and the existence of the universe with a history of over 10 billion years. If the ZPE in radiation were true physically, then the rate of expansion of the universe should have been enormously larger, and its dynamical evolution very different from that of the observed universe. This is a serious conflict, which cannot be taken lightly. Further, our recent experiments in quantum optics with a novel homodyne scheme clearly indicates the unphysical nature of the vacuum modes. The particles also have ZPE, but that is finite, proportional to the finite number of particles. It struck me that Bose's derivation that rejected the wave modes avoided the infinity of ZPE completely, though that was not the aim of the derivation. Apparently, Bose realized this at some stage later, as I understand from a conversation with Partha Ghose. There is a good case for going back to Bose's approach and reformulating quantum optics and quantum electrodynamics with fresh foundations.

Recently I completed a reconstruction of quantum mechanics without any of the foundational problems, like the collapse of the wavefunction, the quantum measurement problem, and the nonlocality in entanglement[27]. This required 'calling a particle a particle', as a significant half-step. Much like what Bose had done, trusting and insisting on rational consistency is essential in firmly fixing the correct foundations of physics.

## *Concluding Remarks*

It is nearly twenty five years after the first atomic gas Bose-Einstein condensate was created. A subtle prediction by Einstein based on a Bose's radically different way of treating the Planck radiation spectrum has motivated many conceptual and technological advances in the field of atomic physics and atom-light interactions. The fascination with atomic gas BEC and attempts at application to new problems continue. It is expected that this charming ultra-cold quantum state of matter has enough steam to go further in holding the attention of physicists for decades to come.

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