

Bose-Einstein Condensate: Hidden Riches for New Forms of Technology and Energy Generation: Potential For Glimpse into Inner Reality

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With the announcement of the recent successful production of a Bose-Einstein condensate (BEC) of photons, a circle has been completed which started in 1925 with the vision of Albert Einstein and Satyendra Nath Bose – a sustained macroscopic condensed state of matter where all atoms are in the same lowest quantum state. The creation of an all-optical BEC, involving a surprisingly straightforward “tabletop” method which bypasses the normally requisite laser/evaporative cooling equipment and ultra-high vacuum chambers necessary for production of the standard delicate atomic BEC, elevates this phenomenon to a new level well beyond its current perception as mere laboratory curiosity. Accordingly, this development certainly heralds eventual incorporation of atomic and photon BECs as standard operating components of energy-efficient mechanical, optical and electrical systems, implying novel ingenious engineering protocols amenable to all the tools of non-linear and quantum optics. Pointing towards such a promising technological future are the suggestion that a photon BEC could serve as a new high-energy ultra-violet (UV) laser photon source, as well as the recent unprecedented implementation of a closed-loop atom circuit (toroidal atomic BEC) demonstrating precise control of superfluid current flow, forecasting the coveted development of an atomic SQUID. Perhaps more significantly, the new highly robust and manageable optical BEC will allow heretofore unfathomable precise probing of the atomic and nano-levels of nature, affording novel high-quality testing procedures of the major foundations of quantum mechanics itself. Such a primary advancement, providing a clearer glimpse into the microscopic realms, may present us as never before with an unprecedented view of the quantum engine that underpins physical reality itself and help place the contextual nature of entanglement and quantum superposition on a firmer foundation. Thus, further progress in achieving mastery over the precise flexible manipulation of BEC states could demonstrate that quantum contextuality might be an unsuspected over-arching archetypal principle in nature, leading to new insight in regards to the interpretation of quantum mechanics as applied to all levels of nature.

1. Introduction

It would be fair to say that few developments in physics in the last decade have made an impact on the practice and philosophical foundations of quantum mechanics, and in so doing has captured the imagination of experimentalists and theorists alike, more than the new state of matter known as the Bose-Einstein condensate (BEC). Because of the wealth of new phenomena which the condensates display, and the precision and flexibility with which they can be manipulated, ever since they were first produced in 1995, interest in them has grown explosively in communities of experimental atomic physics, quantum optics, many-body physics and theoretical physics as well. For instance, the fact that the BEC is capable of greatly slowing the propagation speed (group velocity) of an electromagnetic signal due its capability of greatly altering the local refractive index of an electromagnetic medium, such as in a laser, has sharpened the understanding of the foundational limitations of the special theory of relativity. Indeed, the properties of a Bose-Einstein condensate in a Lorentz-violating scenario, characterized by a deformation in the dispersion relation, is already under investigation. Similarly, the possibility of detecting and monitoring the temperature of a free-falling BEC as a precise test of the strong Einstein Equiva-

lence principle (EEP), a foundation of general relativity, is also to be addressed. In a cross-disciplinary fashion, the emergence of BEC grounded protocols has provided an unprecedented milieu for new precise testing procedures to examine the tenets of both quantum and classical physics.

Moreover, concurrent with these developments, a new technological infrastructure has emerged that was not in place prior to this era, devised by the ingenuity and technical expertise of the experimenters, in order to provide the efficient production and precise controllability of this exotic matter state. For instance, before 1995 when the first BECs were produced, no personnel in the field knew how to operate high-current power supplies for magnetic traps, or had done absorption imaging to take shadow photographs of atoms - both of which are necessary to sustain the structural integrity, and investigate the properties of BECs, respectively.

Yet, as researchers continue to plumb the dynamics associated with the BEC states, they are gradually coming to realize that certain attributes normally invoked to distinguish various known microphysical phenomena, may not be absolute or immutable, but in fact are properties contingent upon contextual quantum factors. In fact, this paper will put forth the argument, that far beyond these impressive technological applications cited above,

this new state of matter may provide the springboard for fueling a philosophical as well as a technological revolution in the very foundations of physics itself. Indeed, it may provide a means as yet unexploited, for humanity to glimpse, as never before, the inner workings of nature as it is exemplified by the quantum engine that underpins physical reality. Specifically, it will be advanced that these BEC states, if manipulated in a certain manner to be described, may reveal the actual primordial nature of many of the standard yardsticks currently used to ascertain and circumscribe physical reality – space, time, energy and matter. Additionally, speculative protocols will be posited, that when properly implemented could also unveil BEC dynamics as the actual engine behind many of the phenomenological anomalies currently beyond the pale of accepted paradigms. For instance, the inexplicable but documented evidence of the efficacy of low-energy nuclear reactions (LENR) – as represented by the process formerly termed “cold fusion” – might be duly accounted for and significantly improved on.

2. Historical Context

However, for many decades the existence of the BEC, which is now a standard tool of experimental and theoretical physics, was only a theoretical possibility. The notion of Bose statistics dates back to a 1924 paper in which Satyendra Nath Bose used a statistical argument to derive the black-body photon spectrum. Unable to publish his work, he sent it to Albert Einstein, who translated it into German and subsequently got it published [1]. Einstein then extended Bose’s counting statistics to the case of non-interacting atoms [2,3]. The result was Bose-Einstein statistics, a standard feature of all particles exhibiting integer spin. Einstein noticed a peculiar feature of the distribution of the atoms over the quantized energy levels predicted by these statistics and then predicted a phase-transition for spin-one bosons. At very low but finite temperature a large fraction of the atoms would go into the lowest energy quantum state. In essence, a separation is effected – one part condenses, the rest remains a saturated ideal gas. This phenomenon we now know as Bose-Einstein condensation. The phenomenon appears naturally as a consequence of quantum statistical effects and represented a modification of the concepts of Bose about the photon energy occupation distribution with no fixed total particle number. Einstein extended and generalized Bose’s notions to a fixed particle number. The condition for this to happen is that the atomic phase-space density must be greater than approximately unity, in natural units. Another way to express this is that the de Broglie wavelength, $\lambda_{DB} = h/(2MkT)^{1/2}$ of each atom must be large enough to overlap with its neighbor, or more precisely, λ_{DB} is the position uncertainty associated with the thermal momentum distribution and increases with decreasing temperature T , with k the Boltzmann constant, h the Planck constant and M the atomic mass. When atoms are cooled to the point where the de Broglie wavelength is comparable to the interatomic separation, the atomic wavepackets overlap and the indistinguishability of particles becomes important. At this temperature, bosons undergo a quantum-mechanical phase transition and form a Bose-Einstein condensate, a coherent cloud of atoms all occupying the same

quantum-mechanical state. The transition temperature and the peak atomic density n are related as $n\lambda_{DB}^3 > 2.612$.

However, confronting the physical ramifications of the conceptual notion of indistinguishable bosons can be disquieting. To quote Einstein: “The molecules are not treated as statistically independent... and the differences between distinguishable and indistinguishable state counting...express indirectly a certain hypothesis on a mutual influence of the molecules which for the time being is of a quite mysterious nature”[3]. Moreover, not only does the Bose-Einstein phase transition offend our sensibilities as to how particles should best distribute themselves, it also runs counter to an unspoken assumption that a phase transition in some way involves thermodynamic stability. In fact, the regions immediately above and below the transition in dilute-gas experiments are both in the thermodynamically forbidden regime. In any generic phase diagram, the Bose-condensed region of the n - T plane is utterly forbidden, except at such high densities, that all known atoms or molecules would form a crystalline lattice, ruling out Bose condensation.

In the normal state of affairs of our daily experience, we deal with three phases of matter: solid, liquid and gas. A fourth, high energy phase of matter, plasma, occurs in many high energy processes, as prosaic as a fire or in an astrophysical context as in the core of a star. We distinguish among the phases of matter in several ways. On the most elementary level, solids have fixed volume and shape; liquids have fixed volume but not fixed shape and gases have neither. Solids have stronger intermolecular bond structure than their corresponding liquids, which in turn have stronger intermolecular bond structure than gases. We can also differentiate between phases of matter by considering energy levels. Solids have the lowest energy levels, while liquids and gases have increasingly higher levels. At the top of the energy scale are plasmas, which are energetic enough to emit energy in the form of heat and photons. BEC represent a 5th phase of matter beyond solids, are less energetic than solids and are hence more ordered than solids in that their restrictions occur not on the molecular level but on the atomic level. Atoms in a solid are locked into roughly the same location in regards to other atoms in the area. However, atoms in a BEC are locked into all of the same attributes; they are literally quantum mechanically indistinguishable in the same location and with the same attributes. When a BEC is visible, each part is the sum of *portions* of each atom, all behaving the same way, rather than being the sum of individual *whole* atoms, as in the other phases of matter. Similar to the counter-intuitive nature of quantum entanglement and quantum superposition, such facts greatly conflict with conventional ideas associated with our standard perception of physical substance.

According to these everyday notions about physical matter and accepted thermodynamical tenets alluded to above, it was therefore not hard to understand that Einstein’s original 1925 prediction was not taken seriously, even by Einstein himself, until Fritz London [4] and Laszlo Tisza [5] resurrected the idea in the mid 1930s as a possible mechanism underlying superfluidity in liquid helium-4. Their work was the first to bring out the idea of a BEC displaying quantum behavior on a macroscopic scale, the primary reason for much of its current attraction. Although a source of debate for decades, it is now recognized that the remarkable properties of superfluidity and superconductivity in

both helium-3 and helium-4 are related to BEC, even though these systems are very different from the ideal gas considered by Einstein. However, the relatively strong interactions between helium molecules lead to a reduction of the ground state occupancy, providing a significant challenge on the direct observation of a condensate. Consequently, researchers turned to considering weakly interacting Bose gases to maximize the fraction of particles in the lowest energy state, known as the ground state. The major problem, therefore, appeared to be the low temperature limit, in which increased molecular forces bind the gas molecules together to form liquids or even solids, violating the assumptions of a dilute limit.

Creating a BEC is simple in principle: cool a gas until the thermal de Broglie wavelength is roughly the inter-atomic distance. However, in almost all cases, the BEC phase transition is preempted by the more familiar phase transitions that lead to liquids or solids. Interactions then localize the atoms that prevent the formation of a BEC. This more conventional condensation can be avoided only at extremely low densities, about one-hundred thousandth the density of normal air, so that the formation time of molecules or clusters of three-body collisions (which is proportional to the square of the inverse density), is increased to seconds or minutes. It is precisely a matter of differing time scales for different sorts of equilibrium. A gas of atoms can come into kinetic equilibrium via two-body elastic collisions, whereas it requires three-body collisions to achieve chemical equilibrium (i.e., to form molecules and then solids). Because the rate of binary elastic collisions drops only proportionally to the density, these collisions are much more frequent and permit the gas to equilibrate within about 10 ms, so that the degeneracy can be achieved in an effectively metastable gas phase. However, such ultralow density lowers the temperature requirement for quantum degeneracy into the nanokelvin range. The density n at the transition temperature is typically 10^{13} cm^{-3} (which corresponds to the density of a room temperature gas at a pressure of 10^{-3} mbar), and the transition occurs at sub-microkelvin temperatures. To put these data in perspective, the so-called Cosmic Background Radiation (CMB) in the deepest space is a "balmy" 3° Kelvin.

The experimental studies on dilute Bose gases date to the 1970s when various laser techniques such as laser cooling, magnetic and optical trapping, had been developed. It was discovered that it would be possible to influence the necessary ultracold collision dynamics using external fields. The extremely low temperatures afforded by laser-cooling meant that the range of energies participating in a collisional event would be extraordinarily narrow. Resonance phenomena could then be used to influence the whole of the gas rather than a small fraction of it, as is the case for room-temperature atomic collisions. The compression of the occupied phase space changes the nature of the collisions from essentially incoherent thermal processes to coherent ones affecting the quantum dynamics of the system as a whole. This coherent dynamics is subtle and complex and fully accessible to external probes and manipulation. In view of these considerations, the cooling procedure was performed essentially in three steps: first, the gas was put in a dilution refrigerator to lower the temperature of the molecules. Subsequently, laser (Doppler) cooling pre-cools the gas so that it can be confined in a magnetic trap. This was succeeded by trapping it in an external magnetic

field aligning the probe spins. The aim associated with laser cooling is to get the atom to absorb mainly photons that are travelling in the direction opposite that of the atom's motion, thereby slowing the atom (cooling it). Evaporative cooling, utilizing a magnetic trap was finally used to lower the gas temperature even further. In the 1980s the major breakthrough in laser technology permitted refinement and improvement of the techniques mentioned above merging the last two steps to a single one, called magneto-optical cooling. The 1997 Nobel Prize was awarded for the development of the laser cooling and trapping methods that are essential for atomic BEC. Further temperature decrease provided by forced evaporative cooling causes the depth of the magnetic trap to be reduced allowing for the most energetic atoms to escape while the remaining atoms rethermalize at progressively lower temperature [6]. Cooling by evaporation is a process found throughout nature. However, the rate of natural evaporation and the minimum temperature achievable are limited by the particular value of the work function of the evaporating substance. However, in magnetically confined atoms, no such limit exists, because the work function is simply the height of the lowest point of the rim of the confining potential. By perturbing the confined magnetic fields, one can then make the work function arbitrarily low: as long as favorable conditions persist, there is no lower limit to the temperatures available in forced evaporation. For a dilute gas, in an inhomogeneous potential, decreasing the temperature will decrease the occupied volume. One can thus actually increase the density of the remaining atoms by removing atoms from the sample. The all important (for BEC) phase-space density is dramatically increased as this happens because the density is rising while temperature is decreasing. The 1997 Nobel Prize in physics was awarded for the development of the laser cooling and trapping methods that are essential for atomic BEC. These experiments also revealed the hidden condensation potential of alkali atoms and their cooling-favoring structure. This statement might seem rather odd since alkali atoms have half-integer total spin rather than the bosonic integer spin requirement. Indeed it is true that the chemistry of the alkali systems at room is principally determined by the electronic properties, which is essentially fermionic since at room temperature thermal excitations have typical energy values much higher than the hyperfine values. However, the bosonic behavior occurs from a subtle interplay of electronic and nuclear spins: at ultra-low temperatures and corresponding excitation energies, the half-integer total spin of the electronic shell and half-integer spin of the nucleus of the atom are coupled by a very weak hyperfine interaction. The total spin of the atom from this coupling is an integer value leading to the bosonic ultra-low temperature behavior of the atom. In addition, the alkali atoms were expected to have well-defined and relatively easy to access optical transitions due to the $1s$ orbital being singly occupied which, combined with the transition rules dictated by conservation of angular momentum, opened the door to controlling the internal energy of the system. Hence by the late 1980s, the temperature of an alkali gas was enabled to be reduced to several micro Kelvins.

This successful trend was continued in the 1990s when the research teams led by Wolfgang Ketterle at MIT and Carl Wieman and Eric Cornell at Boulder, CO, finally reached the critical temperature of sub-microkelvin/few hundred nanokelvin necessary

for BEC to be observed. The first condensates consisted of Rb-87, Na-23, Li-7, succeeded by spin-polarized H, metastable He-4, K-41 atoms, and many others. The successful cooling procedure turned out to use laser-cooling and pre-cooling only. This already achieves ultralow temperatures. The gas is then confined in a magneto-optical trap. Evaporative cooling is used as a final step to decrease the temperature below the critical one ultimately enabling a condensation. This major success culminated in the 2001 Nobel Prize going to Cornell, Ketterle and Wieman 'for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates' [7,8].

3. Manipulation of Light: The Bose-Einstein Condensate as a Medium for Quantum Control in Macroscopic Regimes

Discoveries during the first decade of the millennium have brought surprises and revelations in regards to our previous limited understanding of the properties associated with even phenomena normally relegated to the classical macroscopic realm of mainstream physics. In particular, some of these effects relate to the new means to technologically control the propagation attributed of light: refraction diffraction, dispersion and especially the speed and transmission of a signal. The most remarkable of these advances pertain to the last of these characteristics – the precise control of speed of a signal, particularly the recent achievement of slowing light to a crawl and ultimately ‘storing’ or stopping the progress of light for a few seconds [9]. It is especially significant that the Bose-Einstein condensation phenomenon has been instrumental in providing the means to actually accomplish such feats. In this context, the BEC has been used in an unprecedented manner to produce an enormously varying index of refraction of laser light, subsequently creating a huge reduction in the speed of light. Lene Vestergaard Hau and her team [9] achieved their success by utilizing a special system consisting of a sodium atom BEC at about 50 nanokelvins bathed in two beams of laser light. The first beam continuously shined through the width of the BEC cylinder cloud. This controls the speed of a second pulsed laser beam, subsequently shot along the length of the cloud. While the second laser pulse is in the atom cloud, its group velocity and spatial extent are both proportional to the intensity of the coupling field and inversely proportional to the atom density. The first laser therefore sets up a quantum interference between the two beams of laser light, creating a huge index of refraction, an accompanying phenomenon called electromagnetic transparency in the cloud, and slowing of the group velocity of light by a factor of 20 million.

Despite these tremendous advances, such phenomena produced by BEC states are still primarily considered a laboratory curiosity, and practical technological applications of these exotic states is apparently still a long way off. Nevertheless, finding new ways to control light may pave the way for protocols that use light in this manner to store and transmit information much more efficiently and at lower power than contemporary methods. Moreover, there are the as yet unexploited profound theoretical ramifications surrounding such developments pertaining to further demonstrations of the contextual aspects of nature in the

quantum arena. The mere fact that in the BEC state atoms mimic the coherent nature of photons in a laser provides an important clue to certify this connection. Also, through proper appreciation of this connection, certain technology implemented may provide us with a more profound understanding of the primordial nature of light itself.

In this regard, this researcher speculates that the newly discovered properties of BEC might possibly lead to better understanding of the origin of the universe itself, if it becomes possible to construct a refracting telescope with a non-matter plasma-trapped BEC serving as a lens. It is speculated that the use of a non-matter BEC lens might provide the means to transmit non-visible radiations from possible dark matter sources as well as magnetic fields from stellar radiation, black holes, etc. Given the enormous refractive indexes that can be produced using BECs, which are of several magnitudes greater than that of the ophthalmology-grade glass currently used as optical lenses in telescope construction, the smaller or compact the telescope can be made, compared to one made with lenses with a lower refractive index – even if both of them are rated with the same powers of magnification. However, at present, the near absolute zero requirement for temperatures of BEC renders impractical the construction of such a telescope with magnification ability comparable to say the Keck telescope in Hawaii, since the cooling system to maintain the structural integrity of such a BEC lens would have to be the size of St. Paul's Cathedral. Nevertheless, this proposal is presented in hopes that physicists will be able to surmount these problems in the future to produce a viable prototype to inaugurate an era hallmarked by the unprecedented probing of the mysteries of the universe via the first historical application of what could be termed “quantum sight”.

4. New Source of Light: Photon Energy as BEC Structure

Pursuant to the above conjectured innovations, recently even more astounding developments in this field have shown photons displaying BEC character, to mimic atomic structure. These remarkable recent revelations, challenging the assumed characteristics of the BEC have emerged from the unprecedented empirical demonstration of something heretofore thought impossible – the formation of a *non-atomic* Bose-Einstein distribution from the photonic energy of light radiation [10]. Yet, radiation in thermal equilibrium with cavity walls does not exhibit the phase transition commonly associated with the chemical potential of conserved atomic matter in standard BECs. In such systems, photons have vanishing chemical potential, meaning that they are not conserved when the temperature of the photon gas is varied. To build the customary BEC, atoms must usually collide with each other to even out their temperature. But photons, even those with a slight mass, interact too weakly to do this. However, in this benchmark experiment, by confining light within the narrow space between two barely separated mirrors, and filling the slab-like cavity with a red liquid dye material, the Jan Klaers group [10] achieved thermal equilibration of light as a gas of conserved particles, rather than ordinary blackbody radiation. The cavity mirrors provide both a confining potential and a non-vanishing effective photon mass, making the system formally equivalent to

a two-dimensional gas of trapped massive bosons. Only those photons resonant with the dye and the mirrors' separation – 1.5 μm along their center, or just 3.5 wavelengths – are supported by the cavity. This restricts their energies to a minimum cutoff of 2.1 eV or higher. Because those energies are so much greater than the dye's thermal energy (1/40 eV), spontaneous thermal excitation of photons is negligible. So, although the number of photons can change locally during the exchange of energy and momentum with the dye, the mean number is not determined by dye temperature, as in a standard Boltzmann distribution, but entirely by the pump laser intensity. The cavity geometry and the dye's absorption and fluorescence properties also limit the scattered photons to just one longitudinal electromagnetic mode of the cavity. But they are free to vary among several transverse modes as they equilibrate with the dye heat bath. In this way, the added dye molecules absorbed and re-emitted the photons from the laser fired at the cavity, assisting them in achieving thermal equilibrium. By pumping more photons into the cavity, a critical point is reached where extra photons, prevented from entering thermal equilibrium, undergo a quantum transition, dropping into the same low energy state and forming a BEC. When the low-energy photons at the center of the cavity reached a density of about a trillion photons per cubic centimeter, they began to act as a single photon, shifting in appearance from a blurry glow to a bright point. Above a threshold of about 6.3×10^4 photons in the cavity, a sharp peak emerges at the cutoff wavelength, a signature of photons going into the lowest energy transverse mode. The BEC emission from that TEM_{00} mode appears as the bright spot against a diffuse thermal background. Moreover, because of the miniscule effective photon mass ($h\omega_{\text{cutoff}}/c^2 \sim 10^{-35}$ kg.), the photon gas can exhibit quantum effects and reach BEC phase transition at relatively high ambient temperatures. Consequently, key to important new BEC protocol, this feat was achieved without use of the customary cumbersome laser cooling techniques that are normally a prerequisite for the formation of the atomic BEC. The Klaers work was carried out at room temperature.

Along the same lines, compared to more commonly encountered states of matter, atomic BECs are extremely fragile. The slightest interaction with the thermal environment can be enough to warm them past the condensation threshold, eliminating their interesting properties and forming a normal gas. Contrary to these standard atomic BEC drawbacks, such new understanding associated with the reality of photon BECs and the possible non-requirement of hard to maintain ultralow temperatures for their sustained delicate existence, will undoubtedly be instrumental in transforming the current view of BECs as mere lab curiosities to perception of their possible full-fledged status as operating components of energy-efficient mechanical, optical and electrical systems (see the following section). Accordingly, this new development sheds fresh light on the efficacy in producing various future mass-produced technological applications, such as the proposal above regarding the 'quantum telescope', plus a possible alternative way of generating laser beams, as well as the long-sought after quantum computer. Along these lines, Martin Weitz of the Klaers group has commented that this work could help further shrink electronic devices. Ultraviolet light (UV) has a short wavelength, making it an ideal tool to burn small patterns into computer chips. But UV lasers are difficult to make. If UV

photons can be cooled in the same way that the optical photons in this study were, a photon BEC could serve as a new high-energy UV photon source, Weitz says. A personage no less august than Wolfgang Ketterle, previously mentioned as Nobel Prize recipient in physics for leading the research group that first generated a BEC with atoms in 1995, describes the work as a "spectacular work of physics that removes one more distinction between atoms and light".

5. Control of Superfluid Flow in a BEC: An 'Atomtronic' Circuit

An even more extraordinary practical technological advance in the manipulation of a BEC has emerged with even more recent research that has implications which strongly support and corroborate the theme of this paper. In spring 2011 researchers have established, for the first time, fairly precise control - in terms of being able to start and stop - the rotation of the superfluid state in a toroidal sodium Bose-Einstein condensate medium [11]. The frictionless rotating quantum matter wave actually simulates the role of electrons (Cooper pairs) in superconductivity, and thus opens the door for the possible utilization of BECs as essential circuit elements for future means to afford the efficient transformation and transmission of energy. This new methodology, which has been termed 'atomtronics' by scientists, could also set the stage for a new generation of ultracold-gas-based precision sensors. In this regard, scientists have already produced electronic-based superconducting quantum interference devices (SQUIDS) employing superconducting electrons in a loop to make highly sensitive measurements of magnetic fields. In atomic Bose-Einstein condensates, researchers have previously created Josephson junctions – a thin barrier separating two superfluid regions - in a single atomic trap. One of the aims in creating matter-wave analogs of electronic circuits is towards the eventual development of an ultracold-gas version of a SQUID which could detect condensate rotation. The present work represents an important step in this direction since it involves the implementation of an atom circuit, containing a superfluid ring of current and a tunable "weak link" barrier.

In the new experiment, the research team created a toroidal condensate by cooling sodium atoms almost to the point of quantum degeneracy in a magnetic trap which were then transferred to an optical dipole trap created by the intersection of a red-detuned (1030 nm) "sheet" and "ring" laser beams. The horizontal sheet beam has a vertical (horizontal) half-width of 9 μm (400 μm), and provides vertical confinement for the condensate. The vertical ring beam is Laguerre-Gaussian and confines the condensate to its 20 μm radial intensity peak, generating a toroidal potential minimum. With the atoms in this optical trap, the beam intensities are then ramped down to force evaporative cooling. Circulation of the initially non-rotating condensate is attained by transferring quantized angular momentum from optical fields during a Raman process. The angular momentum change of the condensate is determined by the spatial mode of the Raman beams. Circulation is detected by releasing the condensate from the trap and imaging the density distribution after several milliseconds time-of-flight. If the condensate is not rotating, the central hole closes after a short time. However, when a rotating con-

densate is released, the angular velocity of the flow prevents complete closure. It is the persistence of the central hole after sufficiently long time-of-flight which is the signature of circulation in the ring. Persistent flow – occurring for a record high 40 seconds in this experiment – is a hallmark of superfluidity. The method used to start and stop the flow was via a circuit element – a so-called weak tunable link. This repulsive barrier is created with a blue-detuned (532 nm) laser beam focused to an elliptical spot. The barrier depletes the local density of the condensate increasing the azimuthal velocity of the atoms, thus constituting a tunable “weak link” that can turn off the current around the loop. Superflow stops abruptly when the barrier strength is sufficiently high. When the condensate velocity reaches a critical value, the atoms encounter resistance to flow (viscosity) and the circulation stops. The researchers described the system as “the first realization of a nontrivial closed atom circuit, demonstrating precise control in both inducing and arresting superfluid flow [11], and is a significant step in setting the stage for production of an atomic SQUID analog.

As well as the above being landmark achievements in themselves, making photons behave thermodynamically as atoms, even to the point of Bose-Einstein condensation [10], as well as establishing control of circulation of a toroidal matter-wave [11], illustrates a broader theme in physics complementing the major theme of this author’s current and recent companion papers [12,13] as well. As noted above, atomic gases have been made to behave as laser light [26] and now, conversely, photons have been shown to mimic atomic structure, and most amazingly atoms (bosons) may now be able to play the role of electrons (fermions) in a tunable circuit. The discernible trend is that in terms of the underlying contextual quantum engine possibly underpinning physical reality, everything is becoming, or at the very least is capable of masquerading as everything else. Beyond space and time we may find that physics could be the *art* of the interchangeable. But in the proliferation of these startling masquerades, physical science is also taking on more than ever the aspect of *creative art*, in a medium that, with the advances of modern technology, is proving far less constraining than it once seemed.

Moreover, the fact that photonic BEC energy [10] and Bose condensation of the quanta of magnetic excitations (magnons) [14], have both been recently shown to manifest at room temperature, obviating the necessity for cumbersome laser-cooling/evaporative-cooling hardware, leads us to suspect that these microphysical dynamics may be more ubiquitous in nature than is currently thought. Accordingly, condensate dynamics may possibly play a key role in other related room-temperature energetic phenomena, particularly those exhibiting documented persistent unexplained anomalies that are currently unable to be produced on demand.

6. BEC Model for Lattice-Assisted Nuclear Reactions (LANR)

One of the most controversial of these is the low-energy nuclear transformation process originally termed “cold fusion” (CF). This paradigm revolution was inaugurated in 1989 through the corresponding work of Pons and Fleischmann [15]. It imme-

diately ignited a virtual firestorm of controversy and instant notoriety for these researchers, whose work was not consistently reproducible. This research was summarily discredited by mainstream physics, which continues to this day to stringently uphold the thesis that nuclear fusion can only occur at high energies. However, over the two decades since this phenomenon surfaced, continued research in this frontier field of energy research has shown unquestionably that low-energy nuclear reactions are genuine, and that accompanying excess energy, excess power gain, commensurate helium-4 (alpha particle) production, and minimal neutron particle emission are undeniable, heralding an important new clean form of energy production: fusion assisted by highly loaded metal hydrides. Also, since the reactions occur exclusively on the metal surfaces, afforded by the loading of its lattice sites by deuterium or hydrogen, as opposed to its bulk, the process has been more appropriately termed: Lattice-Assisted Nuclear Reactions (LANR).

As an important byproduct of the eventual demonstration and certification of the viable nature of LANR, physicists have accordingly determined that the original difficulties associated with sustained energy production in the early studies of LANR can be attributed to several factors: (1) the complexities of the experimental set-ups involving many materials (including impurities), (2) numerous variation of experimental and input parameters, (3) poor loadings and a poor appreciation of the requisite metallurgy and engineering, (4) the reported effects were small effects. This situation has prevented the development of a coherent theoretical understanding or working theoretical model of the phenomenon, which can be used as a guide in carrying out new experimental tests to sort out essential parameters and controls needed to achieve reproducibility on demand.

An accurate assessment of the current status of this research, which shows convincingly the adequate resolution of most of the above problems, has been sufficiently disclosed at this year’s CF/LANR Colloquium at MIT [16]. The presentation by one of the most prominent LANR researchers, Prof. George Miley, is particularly notable [17]. Miley chronicles his research both with multi-layer thin palladium (Pd) films after deuterium (D) loading, as well as his earlier studies involving the widely publicized 2 KW “Patterson Cell” which used light water/nickel (Ni) or nickel-palladium composite electrodes. In view of Miley’s duplication of Patterson’s impressive excess heat results, Miley carried out a detailed study of the trace elements formed in the electrodes after many hours of run time. This revealed that much of the energy released was associated with nuclear reactions (transmutations), versus conventional fusion reactions, the latter being hard to understand with light water.

Moreover, pertinent to the claims in the current paper, in his recent power point presentation given on research with alternate Pd-Ni layers and surface deuterium cluster formation, Miley claims, citing the research of Yeong E. Kim [18], that this “high density deuterium cluster formation (pseudo-Bose-Einstein condensation) occurs at room temperature and is fundamental as a way to create nuclear reactive sites for LENR” [19]. The essence of this proposed dynamics is further crystallized by Kim who describes the concept of nuclear Bose-Einstein condensate for mobile deuterons trapped in a micro/nano-scale metal grain or particle, which acts as a confinement or trapping potential, similar to

a magnetic trap customarily used to observe the atomic BEC [20]. If the number density of mobile deuterons in the metal (Pd) can be increased to a comparable density of metal atoms, the average distance d , between the mobile deuterons can be substantially reduced. This may provide an alternative experimental technique for achieving the BEC requirement $\lambda_{DB} > d$, by increasing mobile deuteron density (thus reducing d), rather than cooling mobile deuterons (for increasing λ_{DB}) as was done in the atomic BEC experiments [20]. Kim claims these ideas are not without precedent, citing the first experimental test of the BEC mechanism for deuterium fusion with nano-scale Pd particles was carried out with Pd blacks loaded by high-pressure deuterium gas [21]. However, the result of this experiment showed no excess heat production. Kim attributes this result as due to the fact that Pd nanoparticles used had too large sizes (80-180 nm) and were clumped together. The recent report of deuteron gas loading experiment by Arata and Zhang [22] show positive results of observing excess heat and He-4 production using ~5 nm Pd particles imbedded in ZrO₂ and purified deuterium. For experimental tests of the predictions of the theory Kim suggests it would be advantageous scientifically to use samples of Pd nanoparticles deposited on thin films such as Al₂O₃/NiAl, even though bulk materials such as Pd nanoparticles imbedded in SiO₂ aerogels are more suitable for practical applications. In all cases, the theory requires that metal nanoparticles and micrograins are to be separated from each other by boundaries.

A primary breakthrough in the scientific field of LANR that has emerged in 2011 is Andrea Rossi's E-Cat (Energy Catalyzer) technology [23]. In essence, by exposing nickel powder to pressurized hydrogen gas, along with a proprietary catalyst, cold fusion nuclear processes are induced, and a huge output of energy is released (~12 KW) in the form of heat. Unlike conventional nuclear power, no radioactive materials are used, and no radioactive waste is produced in the process. The E-Cat also emits no pollution into the environment, consumes only tiny amounts of cheap fuel (nickel powder and hydrogen gas), and has a huge power density. These extraordinary claims were backed up with an abundance of evidence from a long series of tests performed by engineers and scientists of a number of different universities, well over a dozen times. This cold fusion device now is apparently the first of its kind to be employed industrially and with forthcoming marketing, with plans of offering this technology as available to the public in the near future.

Apart from the practical issues in connection with this new development, one might wonder how Kim's nuclear Bose-Einstein condensation theory could explain E-Cat operation since particles involved are not bosons but fermions (possessing non-integer spin), specifically protons (hydrogen nuclei). In this regard, Kim's recent paper [24], offers the following ingenious ansatz to overcome these apparent shortcomings: the theory can explain energy output as long as the Rossi device meets the following two conditions - (1) additives used (the proprietary component) form Ni alloy and/or Ni metal/alloy oxide in the surface regions of nickel nano-scale particles, so that Ni atoms/nuclei become mobile with a sufficiently large diffusion coefficient and (2) local magnetic field is very weak in the surface regions, providing a suitable environment in which two neighboring protons can couple their spins anti-parallel to form a spin-zero sin-

glet state ($S=0$). Relatively low Curie temperature of nickel is expected to help to maintain the weak magnetic field in the surface regions. Kim claims if Rossi's device is operated at temperatures greater than this Curie temperature (~358°C) and with hydrogen pressures of up to ~22 bars, the conditions (1) and (2) may have been achieved in Rossi's device. Essentially, the mobility of Ni atoms/nuclei (condition (1)) is enhanced by the use of an electrical resistance heater to maintain higher temperatures.. This may provide a suitable environment in which more of both Ni atoms/nuclei and protons become mobile, thus creating a favorable environment for the case of two species of bosons (Ni nuclei and composite bosons of paired two protons). If the velocities of mobile Ni atoms/nuclei under the condition (1) are sufficiently low, their de Broglie wavelengths become sufficiently large and may overlap with neighboring two-proton composite bosons which are also mobile, thus creating Bose-Einstein condensation of two species of bosons. This dynamics can now be applied to these two-species of bosons and would provide a mechanism for the eventual required suppression/cancellation of the Coulomb barrier, as Kim has expounded on more technically in [25]¹.

¹ Note: other possible models have been invoked to explain E-Cat results, such as water cavitation (Moray King, private correspondence).

7. Conclusion and Prospects

For those who have kept current with the recent literature on the subject of Bose-Einstein condensate research - especially with the explosion of interest and corresponding wealth of knowledge this experimentation has engendered since this exotic matter state was produced in 1995 - it is clear that the bulk of these articles/papers have primarily dealt with the technical aspects of the control and observation of the BEC interaction dynamics, and extolling of its virtues as an excellent tool or testing ground for examining the established principles of both quantum and classical physics. As a departure from this focus, the selected topics of the current paper have been carefully selected and crafted to highlight the additional theme that, since its inception, the exotic counter-intuitive properties of the BEC, and its apparently unlimited scope of application, has blurred the standard classically-based distinctions that are presumed to exist between various elements of microscopic reality. Indeed BEC dynamics has been shown to mimic photons in a laser [26], photon BEC can exhibit the behavior of atomic particles [10,27], and most amazingly, superfluidity of atomic BEC can possibly play the role of electrons in a superconducting circuit [11]. The purely scientific merit in this trend is that demonstrating the interchangeability of these properties clarifies a few universal patterns and principles that really are conserved and possibly represent true archetypes. One of the Nobel Prize winners for early BEC research, Wolfgang Ketterle, put it best in his 2002 *Nature* "Insight" article [26] - "The field is now at a historic point, in which we are moving from studying physics to learn about atom cooling, to studying cold atoms to learn about physics". I would add to this that now there is the potential for BEC research to reveal not only new physics itself, but the possible archetypes that are at the foundation of the quantum engine that underpins physical reality. Indeed, like no

other phenomenon in recent history since the laser and the advent of superconductivity and superfluidity, the exotic BEC state has revealed, via its vast panorama of application, the heart and soul of the principles of quantum mechanics – the supposed theory of microscopic reality – displayed in all its glorious form on a macroscopic scale. The contention of this paper is that perhaps this is not just a quaint coincidence, but is pointing science to consider a possible deeper connection between this unique state of coherent matter and the primordial nature of reality beyond time and space.

Accordingly, a suggestion has been made which bears repeating as to how this currently unfathomed possibility could be made manifest. On the basis of the extraordinarily large refractive index which can be produced by the BEC state by low-energy laser radiation, perhaps a super high-tech refracting telescope could be built utilizing a plasma-trapped non-matter BEC as its focal lens, thus allowing for the possible transduction and passage of non-optical radiation, consequently greatly expanding our understanding of the universe and our place in it. In particular, knowledge obtained from this protocol – what might be called the first application of “quantum sight”, via this unprecedented hybrid matter-non-matter device, might help solve current astrophysical mysteries, such as the hypothesis of dark energy invoked to account for the accelerated expansion of the universe and the equally puzzling non-Newtonian “flat” rotation rates which is a feature of galactic dynamics but not solar system mechanics.

As possible icing on the cake, recent key studies on LANR research has been cited to show the distinct possibility that documented robust energy and power yields such as in the protocols examine in the research of George Miley [17,19] and Andrea Rossi [23], might be due to the formation of two species of room temperature Bose-Einstein condensates due to mobility of deuterons or proton-pairs constrained by the trapping potential of lattice sites on the nano-scale size metal hydride particles – palladium or nickel, respectively. Thus, despite the relatively high ambient temperature, due to the increase of atomic density lowering the interatomic distance and hence reducing deuteron velocities, BEC conditions are permitted to obtain, allowing deuterons/proton-pairs to broach the nuclear Coulomb barrier.

Moreover, this “cold fusion” example of the possible unplumbed evidence of BEC dynamics begs the question as to whether other protocols exhibiting over-unity power that have been so far unreproducible on-demand, could be understood using the BEC model. Most importantly, the non-requirement of expensive laser cooling equipment for the photon-BEC now brings this experimental research possibly within the expertise of even amateur researchers. In this regard, in connection with the recent LANR research discussed, this author suggests that such contemporary unconventional controversial type research could possibly exhibit the coveted on-demand sustained energy production and a higher level of respectability if protocol in association with these experiments were carried out on the nano-scale of matter components. Better results could possibly be obtained, revealing these mechanics and rendered less controversial.

As this paper goes to press, a recent arXiv paper (Jan. 2, 2012) by the Klaers team has theoretically analyzed the temperature behavior of paraxial light in thermal equilibrium with a dye-

filled microcavity [27]. At low temperatures the photon gas undergoes BEC transition and the photon number in the cavity ground state becomes macroscopic with respect to the total photon number. They found that owing to a grand-canonical excitation between the photon gas and the dye molecule reservoir, a regime with unusually large fluctuations of the condensate number is predicted for this system that is not observed in present atomic BEC experiments. As time goes on, such experiments with the BEC state continue to reveal the contextual nature of microscopic reality even more clearly, showing properties of so-called elementary particles might not be as immutable as presumed formerly from scientific perspective at the macro-level of nature, but are possibly contingent upon presently unknown quantum factors of primordial reality – beyond time and space. As a consequence, physical measurable properties and like the customary yardsticks of macroscopic nature could possibly be ultimately variable yielding to intelligent control – BEC manipulation might afford a future means to craft “designer” atoms to make malleable the properties of large objects – to even engineer reality itself; something heretofore thought only as the province of science fiction. Moreover, on a grander panoramic scale, our expanding knowledge gleaned from examining the BEC state, will explicitly shape the future of society as well as science, especially concerning our openness to phenomena that challenge our current belief systems.

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