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A Survey of Atom Interferometer Beam-Combination Configurations and Beam Splitter Designs

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This report summarizes the state of the art of atom-interferometry experiments, with an emphasis on the beam-splitting and beam-combination configurations, as well as on the different choices of beam splitter designs including both the successful and the unsuccessful ones. Analyses and discussions are given on the relative merits of the different types of configurations and designs in the context of the different types of potential applications. The possible causes of the success and failure of the different atom-interferometry configurations are also explored, the ultimate understanding of which is tied to the resolution of the quantum measurement problem and possible ontological foundation for quantum mechanics. The insights gained by a new, heuristic model of the quantum measurement process could be used to guide the design of atom interferometers and the choice of beam splitter configurations. One example of a hybrid design of an atom interferometer incorporating both the free-space and atom-chip-based technologies is given.

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Abstract

This report summarizes the state of the art of atom-interferometry experiments, with an emphasis on the beam-splitting and beam-combination configurations, as well as on the different choices of beam splitter designs including both the successful and the unsuccessful ones. Analyses and discussions are given on the relative merits of the different types of configurations and designs in the context of the different types of potential applications. The possible causes of the success and failure of the different atom-interferometry configurations are also explored, the ultimate understanding of which is tied to the resolution of the quantum measurement problem and a possible ontological foundation for quantum mechanics. The insights gained by a new, heuristic model of the quantum measurement process could be used to guide the design of atom interferometers and the choice of beam splitter configurations. One example of a hybrid design of an atom interferometer incorporating both the free-space and atom-chip-based technologies is given.

1. INTRODUCTION

Atom interferometry was first successfully demonstrated by several groups in 1991[1,2,3] in the free-space configuration, utilizing either material gratings or optical lattices to split and recombine the beams; or else using Raman pulses to interact with the internal degrees of freedom of the atoms to achieve coherent superposition states of atoms that are spatially separated and can thus be interfered. These early efforts was built on the heritage of neutron and electron interferometry experiments carried out decades earlier, and share some similarities with them especially in configurations which utilize the external degrees of freedom of atoms to split the beams (i.e., the material grating or the optical lattices configurations). The utilization of the internal degrees of freedom of the atoms is a feature unique to atom interferometry, as the neutrons and electron do not possess internal degrees of freedom.

The second half of the 1990's saw the successful achievement of Bose-Einstein condensate of alkali atoms using laser-cooling and magnetic trapping techniques[4,5], and the shift in effort towards miniaturization through cooling and guiding the atoms in magnetic or optical waveguides, or the so-called atom-chips[6,7], the hope being that the free-space to chip-based atom guiding transition would correspond to the lumped element to integrated circuit transition in electronics.

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However, despite concentrated efforts by numerous groups worldwide over the past five years on realizing atom interferometry in the chip-based environment, and despite the prior successes of atom interferometry in the free-space configurations, it has proven exceeding difficult to achieve atom interferometry in the guided wave configuration, and as of now no successful coherent beam splitting and beam combination has been demonstrated either for a magnetic or for an optical waveguide of the conventional forking type, for either a propagating atom wave or a Bose-Einstein Condensate[8,9,10].

Recently, there have been reported successes reported by the MIT group[11] and by the University of Colorado/JILA group[12] in separating a BEC into two clumps and then coherently recombine them, either through manipulating a dipole confining potential, or through the optical pulse excitations with a laser standing wave, both in the atom chip environment. However, these rather contrived configurations, both starting with a static BEC clump instead of a propagating atom wave, and both involving two split BEC clumps propagating away and toward each other along a straight line instead of forming an enclosed area, and both working only for BECs and not for cold atoms in general, are expected to be of limited use as atom interferometry sensors (for example, they cannot be used as rotation or acceleration inertial sensors, due to the vanishing of the enclosed area of the interferometer), even after such use can be demonstrated for certain applications (At the present time, both the MIT experiment and the JILA experiment suffered from an extremely short coherence time, on the order of several milliseconds, and the coherent beam separation distance is on the order of 10s to 100 um, instead of on the order of a fraction of a meter as in the case of free-space thermal atom interferometer).

In view of the fact that the decoherence behavior observed in most of the current generations of the guided-atom beam splitters (both the magnetic chip version and the optical/dipole guide potential version) is closely connected to the quantum measurement problem, which is still an unsolved problem more than 70 years after the advent of quantum theory, and which is closely tied to the foundations problems of quantum mechanics, a practical solution of the beam splitter design problem would benefit from empirical as well as heuristic approaches, plus trial and error in the actual experimental setup in order to arrive at a working solution. This combined synthesis approach is what we will adopt in this study, resulting in our choice of a hybrid design of a practical atom interferometer which can be used a wide range of inertial and field sensing applications and is still of modest size.

Another objective of the study is to highlight the often neglected fact that the best interferometer configurations, in terms of sensitivity, tolerance, and expense, are often dependent on one's particular applications. We will present detailed analyses to demonstrate this point.

2. ATOM-INTERFEROMETER BEAM COMBINATION CONFIGURATIONS AND BEAM SPLITTER DESIGNS

In this section we will survey the types of most commonly-used atom interferometer beam combination configurations which also uses different types of beam splitter designs, and summarize their working principles and the types of applications that they have been used in.

Figure 1 shows the working principles of an atom interferometer used for inertial sensing. The inertial sensitivity of an atom interferometer arrives from the fact that if the platform where the interferometer resides on is accelerating, the grating locations has a second order dependence on time, whereas the trajectory of atoms in an inertial frame follows a linear path. Therefore the location of the fringes shifts when the platform is undergoing acceleration compared to when it doesn't.

The sensitivity of the atom interferometer to the electric or magnetic fields, etc. comes from the fact that the phases of the wavefunction in the two arms of the interferometer, in the case of a separated-path interferometer, experience different amounts of phaseshifts if there is a field gradient. Therefore the interference of the wavefunctions after passing through the two arms will once again lead to a shift in fringe location, resulting in the sensitivity to the gradient of fields. Of course, it remains necessary to disentangle the type of fields being sensed from the measured overall fringe shift. Another challenge is on vibration isolation and the reduction of systematic effects so the improved sensitivity of matter wave interferometers (see Berman[3] 1997 and the references therein) over that of light based ones[13] can be truly realized.

2.1 Free-Space Atom Interferometers

The most commonly-used free-space atom interferometer comes in two flavors. The first one is similar to the classical implementation of Young's double slit interferometry in optics, with the gratings used for splitting and recombining the beams made from material gratings. The second type makes use of the interaction of light with the internal degrees of freedom of atoms, and for absorption probability of photons between 1 and 0 the atoms are excited into a coherent superposition state made of atoms partially in the lower atomic state and partially in the upper atomic state, each traveling a different path due to the momentum impact of the photons to those portions of atoms which have been excited to the upper state. Of course, either of these two cases can use thermal or cooled atoms. But so far it has been more typical among the experiments conducted to use thermal atoms for the first type of interferometer and to use cold atoms for the second type.

As an example of the first type of free-space atom interferometer, in Figure 2 we show the sketch of the free-space atom interferometer utilizing material gratings as beam splitters[14] This configuration is the most similar to the classical Young's double-slit experiment, the only difference being that instead of two split, here there is a periodic multi-slit grating which serve to split and recombine the beams. The separated spatial paths of the two beams gives the instrument the sensitivity to field gradients and inertial reference. Only the external degrees of freedom of atoms are involved so in this respect this configuration is also similar to the earlier neutron and electron interferometry setup.

Figure 3 shows one of the possible realizations of the second type of free-space atom interferometer. This configuration was first proposed in context of atomic clock application[15]. In this approach, a beam of atoms or a BEC clump which has been state-prepared to occupy the lower level of a two-level system experiences a so-called pi/2 pulse which leaves the atoms in a coherent superposition of the two-level state. In the case of the optical laser pulses (as opposed to the microwave pulses used in the atomic clock application), there is enough momentum impact of the absorbed photons by atoms going through the level change so that the atoms occupying different internal states are also spatially separated (of course, due to the coherent nature of the superposition state, we cannot assign the identity of atoms to the upper or lower states so clearly). Subsequent free-space propagation and remixing effect by follow-on pulses leads to the interference of the two beams in the superposition state and each leg can experience different amount of phase shift due to field gradient. Likewise it also has inertial sensitivity[1,16,17].

here has been recent attempt using the optical lattice potential to confine cold atoms/BEC directly, and using the release of these lattice-confined atoms and their interference to detect earth's gravity gradient [18] see also Figure 4. However, compared to the separated atom-beam approach the optical lattice approach is likely to be limited in its range of applications.

Other types of free-space atom interferometer configurations include those of Talbot type, Talbot-Lau type, Borde type, etc.. A comprehensive view of these different types of free-space atom interferometers can be gained from the articles in Berman edited “Atom Interferometry”.

2.2 Chip-Based and Optical-Waveguide-Based Atom Interferometers

The atom-chip based and atom-waveguide based atom interferometers share the common characteristics that during the propagation of atom waves, instead of an unconstrained plane wave, the atom wave is distributed in the transverse plane by the confinement of the guiding potential, which in the case of atom chips is provided by the current-carrying wires and the magnetic field it generated, as well as by the substrate, and in the case of the optical waveguides by the optical dipole force of the laser field. The wavefunction of the atoms in these guided situations are no longer plane waves, the motion of the atoms are close to being helical and at any given instant is much more localized in position space than in the free-space case. These differences between the guided atom wave and the free space atom wave may partly account for the difficulty in generalizing the success of the free space atom interferometry experiment to that of the guided-wave atom interferometers.

As we have mentioned in the introduction, so far for all the atom interferometry experiments conducted world-wide in the atom chip or atom optical waveguide environment, none had demonstrated genuine success (see however, the later discussions of the Shin et al.[11] experiments). One of the major roadblocks in realizing guided atom-wave interferometry is in the successful implementation of coherent beam splitters and beam combiners in the atom waveguide environment. In the following we summarize the results of several recent attempts at designing and implementing the atom-waveguide beamsplitters.

Figure 5 shows the beam splitter design used in JILA [9]. In this design a main current-carrying wire guides the input atoms into the beam splitting region. The beam splitter is realized using a secondary wire, at first situated in the vicinity of the primary wire, so the guiding potentials created by the two wires initially reinforce each other. At the end of the interacting region, however, the two wires are gradually separated by a considerable distance, the hope is that this gradual separation of guiding potential will create a coherent splitting of the atom wavefunction.

The performance of the JILA atom chip beam splitter is shown in the next two figures. In Figure 6, a collection of thermal atoms are launched into this waveguide beam splitter. Through absorption imaging it is seen that the intensity of the atom beams are uniformly split by the beam splitter. But individual atoms either went one way or the other, there is no coherence between the two beam paths.

In Figure 7, we shown the response of the atom chip waveguide beamsplitter to propagating BEC clumps. It can be seen now from the absorption image taken that a particular BEC clump, when encountering the discontinuity at the beam splitter junction, either went completely in the upper path, or completely in the lower path. The upper and lower occupation locations are complemtary to each other. There is not a single incident where half of the BEC clump went up and half went down simultaneously. Although manufacturing imperfections are not excluded from the possible causes, the persistent difficulty in coherently splitting the atoms or BECs in this type of atom-chip beam splitter indicates that a quantum measurement effect which causes the wavefunction collapse at the discontinuity of the beam splitter junction may have played a role.

The optical waveguide beam splitter experiments conducted so far corroborate the story given by the atom-chip magnetic waveguide. Figure 8 shows the absorption image of the atom distribution under a two dimensional guiding potential pattern created by interfering laser beams formed by two lenlet arrays. It can be seen that the atom intensity distributions do divide among the different branches of the guiding potential pattern. However, Dumke et al.[8] who had conducted this series of experiments failed to obtained coherent beam splitting by this type of optical guiding potential, for all the beam splitting geometries they tried, including two-way and Mach-Zehnder, despite the fact that theoretical calculations carried out by the same group through the solution of time-dependent Schrodinger equation indicate that coherent beam splitting in this type of geometry should be possible[19]. Once again, as in the case of magnetic atom chip, the quantum measurement effect relating to wavefunction collapse at the discontinuities of the guiding potential is a likely suspect for causing the decoherence behavior.

Amidst the prevalent negative reports on the coherent behavior of guided-atom interferomter beam splitters, there are at least a couple that reported some degrees of success, albeit in splitting configurations far removed from what's usually desired for separate-path atom interferometry. One of these was carried out by the MIT group[11,20]. In this experiment, a Bose-Einstein Condensate (BEC) was created in the atom chip environment. The BEC was subsequently coherently split by deforming an optical single-well confining potential into a double-well potential (Figure 9). Interfering of the two split BEC clumps after their release from the confining potential shows fringes (Figure 10), and the relative phase of the the BEC clumps can be varied by applying ac Stark potential to one of the clumps.

Despite the apparent success of this atom interferometry experiment in the atom chip environment, several issues curtails the optimistic generalization of this limited success to wider atom interferometry applications. First of all, it is not clear that the relative phase of the two clumps maintains the same value for each splitting sequence. As is well known, the effective long coherent length of the BEC (similar to the long coherent length of an optical laser) dictates that two BEC clumps will show interfering fringes even if they are generated independently of each other and are of arbitrary relative phase. This point has been corroborated in an earlier MIT ``atom laser'' experiment [21]: In fact, the Shin et al. experiment is nothing more than a repeat of the Andrews et al BEC interfering experiment in a double-well splitting potential, the only difference being the presence of the chip environment. Without a deterministic, knowable, relative phase between the two interfering paths, the application which will imprint onto one of the two paths an additional phase shift would have difficulty disentangling the application-imprinted phase from the double-well splitting imprinted relative phase. Secondly, the splitting of the BEC clump was done in a static configuration of the atoms, and not in a propagating atom wave configuration as in the usual atom interferometry applications. This prevents the application of this atom splitting approach in many commonly used interferometer configurations which form the enclosed area of the interferometer by the separated beam propagation paths. Lastly, as analysed by Collins et al.[22], the Shin et al. [11] (2004) experiments, despite demonstrating successfully fringe formation, still contain many features which fails to be explainable by the numerical solutions of the quantum-mechanical Gross-Pitaevskii equation. Central among these is the decoherence behavior, which as can be expected is much worse than the theoretical prediction. Once again we suspect that the quantum measurement effects not modeled by the Schrodinger or Gross-Pitaevskii equations are playing a role in this beam splitting configuration.

Another recent BEC splitting and interfering experiment in the atom-chip environment was carried out by the University of Colorado/JILA group[12] (see Figure 11). In this experiment the BEC clump held above the chip surface was split and recombined by applying laser standing wave pulses of fixed durations, which act like optical diffraction gratings [22].

3. COMPARISON OF DIFFERENT ATOM INTERFEROMETER CONFIGURATIONS

The different atom interferometer configurations described in the previous section have advantages and drawbacks depending on the intended applications. The decisions whether to cool the atoms, how much to cool them (i.e., to generate a BEC or not), and whether to use free-space or chip-based configurations, whether to use the internal or external degrees of freedom to split and guide atoms, will all have to be determined by the details of the application, the heritage and expertise of a particular team developing the instrument, and on available funding and resources.

Take as an example the decision of whether to use cooled atoms or thermal atoms to perform atom interferometry. If our application is rotation sensing, for example, the phaseshift due to rotation at angular velocity Ω is given by[23]

$$\Delta\Phi_{rot} = \frac{4\pi}{\lambda_{dB} v}\Omega A ,$$

where $\lambda_{dB} = h / mv$ is the de Broglie wavelength of the atoms, v the longitudinal speed of the atom beam, and A is the area enclosed by the two paths of the interferometer. Furthermore, for a diffractive type of beam splitter, the area A is given by

$$A = L\square L\theta_{diff} = L^2 \frac{\lambda_{dB}}{d_g} = L^2 \frac{h}{mv}\frac{1}{d_g}$$

where L is the separation between the adjacent gratings, θ_{diff} is the angle between the two adjacent diffraction orders used, d_g is the grating period, and m the mass of the atom. Therefore, the phase sensitivity to rotation can alternatively be written as

$$\Delta\Phi_{rot} = \frac{4\pi m}{h}\Omega A = \frac{2k_g L^2}{v}\Omega$$

where $k_g \equiv \frac{2\pi}{d_g}$.

Therefore for the best sensitivity to rotation, we desire large A which appears to be inversely proportional to the longitudinal velocity v, indicating we might want slow atoms. However, in practice the useable grating separation L is constrained by the atom velocity due to the downward pull of gravity, therefore a slow atom beam will generally result in a correspondingly lower useable value of L. Since the L dependence is second order and v dependence is first order in the expression of A, we see that to achieve a large enclosed area, and therefore better sensitivity to rotation, we in fact desire to use thermal atoms instead of cold atoms, or at least atoms which has significant velocity component in the longitudinal direction. Cooling, and especially transverse cooling, however, would benefit signal-to-noise ratio through increased the atom flux. Similar analyses show that the sensitivity of an atom interferomter to acceleration or gravity is also likewise better for an atom interferometer of larger enclosed area, i.e. one utilizing thermal atoms.

The free-space, internal state atom interferometer generally contain smaller area compared to the external state atom interferometer, due to the limited momentum kick of one- or two-photon processes. However, by utilizing a sequence of pulses it is possible to increase the area of the internal state, free-space interferometer as well, so it is not clear that this aspect is its intrinsic limitation. In certain applications, such as atomic clocks the internal state atom interferometer is exclusively used.

As for free-space and chip-based atom interferometers, apart from the fact that so far no genuine chip-based atom interferometer sensor has been successfully demonstrated, even if the existing roadblocks were overcome, it is not immediately apparently that the guided-wave atom interferometers would take over the applications from the free-space atom interferometers as the integrated-circuit industry has taken over the lumped-element circuits. Some of the reasons for this conclusion are the following: (1) The guiding potential (magnetic or optical) introduces perturbation to the internal-state energy levels of the atoms, and for applications whose accuracy depends on the precise knowledge and stability of the energy levels of atoms, these perturbations due to the guiding potential may overwhelm the noise contributions and limit the ultimate accuracy achievable, though the effect of the perturbations could be curtailed through clever selections of atom levels used in the experiments, as in the recent chip-based atomic clock experiments[24]. (2) Since the inertial sensing capability of atom interferometers depends on that atom waves propagate in inertial space, the application of guiding potentials could potentially jeopardize the intrinsic ability of an atom interferometer to perform inertial sensing functions, though some round-about ways may be devised to extract information out of the combined effect of guiding and inertial perturbation. Exceptions to this concern do exist such as in the optical fiber gyro, which apparently does not interfere with the inertial sensing capability of the photons since the effective "friction" applied by the optical fiber to the EM wave is zero,, but such complete lack of impact of the guiding structure to the inertial propagation of the atom wave in the chip environment is yet to be established. (3) The guided atom configuration is intended to be used in conjunction with laser cooling and trapping. As we have commented above, as far as the sensitivity of an atom interferometer is concerned, cooling is not always helpful in achieving the best sensitivity, especially for inertial sensing and gravitational force sensing.

All in all, the lure of the reduction in size and the robustness of packaging makes it likely that further research into integrated atom optics will continue for the foreseeable future, though as we will argue shortly in this report that a hybrid approach combining the advantages of both the free-space and the chip-based configurations may prove to be the most profitable in producing atom interferometric sensors of practical usage.

Other factors, such as easy of construction, size, cost, throughput, and sensitivity to alignment errors should all be taken into account when deciding on the interferometer configuration most suitable for a particular application.

4. A HEURISTIC MODEL FOR UNDERSTANDING THE BEHAVIOR OF ATOMS DURING BEAM SPLITTING/BEAM COMBINATION AND OTHER TYPES OF QUANTUM MEASUREMENT PROCESSES

The experimental work conducted so far on the different types of atom-waveguide beam splitter designs were mostly carried out in a trial-and-error fashion. Due to the lack of a deterministic theory on the quantum measurement process, a one-to-one correspondence between theoretical predictions and experimental results concerning the behavior of the decoherence processes during quantum measurements is beyond reach. Attempts at explaining the observed behavior of atom interferometric experiments using the solutions of the time-dependent Schrodinger's equation or the non-linear Gross-Pitaevskii equation had invariably failed: usually the decoherence behavior observed in the experiments was much more severe than predicted by the theory[22]; or else the coherent beam-splitting and beam-recombination properties expected theoretically was simply not corroborated by the experiments[10].

At the present moment the world community has not given up entirely the attempts at producing working atom-waveguide beam splitter designs, hoping that the failures experienced over the past few years in the prototype beam-splitters were mostly due to manufacturing imperfections, and these difficulties would be circumvented as the techniques for manufacturing beam waveguide components improve. However, the persistent failure of experiments conducted by various groups worldwide, and especially the consistent pattern of failure of coherent beam splitting both in the magnetic atom-chip environment and in the optical atom-waveguide environment, prompt us to take a step back and question whether there are road-blocks at the fundamental physics level, i.e., if the ultimate theory of quantum measurement were obtainable, whether the beam splitter designs so far been attempted contain elements which prevent them from working successfully as a matter of principle.

To that end, in what follows in this section I briefly describe a heuristic model that I have been contemplating on over the past few years on the quantum measurement process and the ontological foundations of quantum mechanics. If this heuristic model turns out to correspond to physical reality, then the different behaviors observed in the different quantum measurement processes, including the behaviors of the different types of atom interferometry beam splitters, can be naturally understood. This model can thus shed light on the choice of the starting configurations of the beam splitter designs, and warn us from the outset what kind of designs are not likely to work as a matter of principle.

This model is based on the assumption that the quantized nature of the fundamental processes is the result of their being resonance phenomena in a giant resonant cavity encompassing the whole universe. A “quantum measurement” process happens as a phase transition in the joint system of object, measuring instrument and the rest of the universe under the proper boundary condition. The quantum measurement processes or “wavefunction collapse” are nothing more than the spontaneous formation of these nonequilibrium resonant modes in the universe cavity. The measuring apparatus enforce a particular kind of boundary condition under which a given modal characteristic of the physical process under investigation manifests. In this picture the quantum measurement process can also happen spontaneously when the proper boundary conditions are met, and does not have to involve a conscious observer.

This view has the following empirical support (not an exhaustive list):

1. The wavefunction of a quantum observable in general spreads throughout the infinite space. A quantum measurement is in general a non-local process, and its result is not determined by the localized measuring instrument alone (as manifested by the probabilistic nature of the measurement results).

2. Quantum measurements happen not simply between the system under concern and the measuring instruments. It also involves the “give and take” with the rest of the universe, as evidenced in the position/momentum pair of measurements (in essence we are not measuring ``the same particle'' anymore in the successive non-commuting measurements). This “give and take” with the rest of the universe accounts for the apparent violation of energy conservation in many quantum measurement processes. It could also explain the paradoxial facts that the accelerated electrons radiate in certain cases (as when they travel freely in straight line) and not in other cases (as when they circulate an atomic nuclei in bound states).

3. The hierarchical order of natural systems is an evidence of the successive non-equilibrium phase transitions which had happened spontaneously in the universe resonant cavity. The spontaneous nature of these phase transitions helps to resolve “Schrodinger's Cat” type of paradoxes, since a naturally occurring “quantum measurement” does not have to involve a conscious observer. The possibility that naturally occurring orders are results of non-equilibrium phase transitions also explains the stability and reproducibility of these natural orders, i.e., the result of the non-equilibrium phase transitions is insensitive to the *details* of the initial-boundary conditions, and depends only on the gross nature of these conditions.

4. The physical laws often follow least action or variational type of relations. This behavior generally reflects the fact that the energy content of the process under concern is distributed globally and samples the environmental/boundary conditions of the entire space it occupies.

5. If values of the fundamental constants are determined by the characteristics of the universe resonant cavity, the variation of the values of these “constant” with time (such as the recent observation of the likelihood of the variation of the fine-structure constant) would be naturally expected if the universe resonant cavity changes with time (e.g. the expansion of the universe).

6. In this picture the vacuum fluctuations are the “residuals” of the making of the “whole” numbers of non-equilibrium quasi-stationary modes in the open, infinite universe cavity (the other examples of such non-equilibrium “dissipative structures” are found in a variety of physical systems, such as the turbulent convection cells or Bernard's instability in atmosphere circulation, or the spiral structure in galaxies).

This provides a possible explanation of why many fundamental physical effects (such as Lamb shifts, Casimir effects, spontaneous emission, van der Waals forces, and the fundamental linewidth of a laser) can be explained equally successfully by adopting either the vacuum-fluctuation point of view or the source-field point of view[25].

7. In this picture the phase of the wavefunction acquires a physical content, and reflects the self-organization of all the matter (and energy) content in the universe and their interrelations. Together with the environmental factors, the phase of the wavefunction determines the exact outcome of a quantum measurement, thus eliminating the probabilistic factor in the current explanation of the quantum measurement results.

8. In this picture the infinite degrees-of-freedom (DOF) offered by the free exchange of energy and matter contents between parts and parcels of the make-up of the universe in wave form leaves open the generation of free will in sentient beings, since the infinitely-sensitive dependence on the details of perturbations of an infinite DOF system leads to the ultimate indeterministic factor in the generation of free will. This indeterministic factor in free will is not to be confused with the quantum uncertainty relation, the latter in our current view is only a result of our lack of knowledge of all the environmental influence on the exact phase of the quantum wavefunction, which when interaction with the wavefunction of the measuring instrument determines the exact outcome of the measurement as a joint wavefunction collapse of the object to be measured, the measuring instrument, and the rest of the universe.

Armed with the physical insights offered by our heuristic model, we next take a closer look at the different types of beam splitter designs used in the atom interferometry experiments, including both the free-space versions and the beam-waveguide versions, and try to understand the causes of the successes and failures of these designs.

The free-space atom interferometers based on manipulating the external degrees of freedom of atoms [14,26] make use of material gratings to split the beams. The incoming atomic beam, being in a momentum eigenstate (i.e., a plane wave), sees a periodic type of boundary condition set up by the grating potential, and responds (as waves do) by diffracting off these periodic gratings. Therefore the extended and periodic nature of these beam splitter/beam combiner leads to the kind of boundary conditions which allow the wave modes remain modes albeit been diffracted into different spatial patterns.

The free-space atom interferometers based on manipulating the internal degrees of freedom of atoms [1] utilize optical pulses of fixed duration to change the upper- and lower-state population ratio of the atoms in the coherent superposition state, and to split the beams. These temporal pulses can in fact be decomposed into spatial-temporal modes which once again makes the effective interaction with the propagating atom waves global, or distributed in space[15].

The success of these two broad types of free-space atom beam splitters leads us to seek the key differences between these configurations and those used for atom-waveguide beam splitter designs, most of which so far have been attempted without success.

One difference we notice immediately is that in the atom waveguide configurations (be it magnetic atom chip waveguide, or optical dipole force waveguide), the incoming waves, rather than arriving in the form of a plane or spherical wavefront, as in the case of the free-space atom interferometers, are confined rather in the narrow "tubes" defined by the waveguide potential. Therefore the particle nature of the atoms is expected to be manifest more severely compared to the wave nature (i.e., with atoms in the position rather than the momentum eigenstate) due to this imposed boundary condition, especially when the confining potential has small-scale irregularities. Furthermore, for the forking type of atom beam splitters, the abrupt physical discontinuity at the beam splitting junction most likely does not correspond to a natural distribution of a single spatial mode of the atom wave, and thus when the incoming wave encounters such a discontinuity, a "wavefunction collapse" naturally happens (if this has not already happened at the incoming waveguide section, which is another possibility), and the atom wave chooses either one leg or the other of the split paths as it collapses onto a localized particle.

One would at this point ask another question of curiosity: Since photons also possess particle-wave duality, why optical fiber beam splitter of the forking type works where it failed for atoms? What is the essential different nature of the photon and atom waves which gives them the different behavior when encountering such a forking discontinuity?

We note here some possible differences:

1. The photon's wavelength and coherent length can be totally different: For a visible wave laser, for example. the wavelength of the photons is on the order of hundreds of nanometer, yet its coherent length could be several meters; whereas for atoms, the coherent length and its de Broglie wavelength are always on the same order, both tied to the momentum spread of the atom wave. The short coherence length of the atom wave could be an important contributor for its vulnerability for wavefunction collapse at the beam splitter. In essence, the spectral (momentum) purity comparable to optical lasers has never been achieved for atoms, even in a Bose-Einstein condensate (which has coherent length and de Broglie wavelength on the order of a micron). So while laser light of coherent length of several meters encounting a discontinuity at the fiber beam splitter of the size of tens of μm, could preserve coherence since the size of this discontinuity is a tiny fraction of its coherent length, similar sized discontinuity in the atom waveguide beam splitter is of comparable size or larger than the coherent length and the de Broglie wavelength of the atoms, and would lead to a wavefunction collapse because of this newly enforced boundary condition.

2.The quantizations of atoms and photons (second quantization versus field quantization) do follow different types of commutation relations, and the possibility is not excluded that there could be intrinsic differences in the atoms and photons wave/particle duality behavior.

Therefore, from the above analysis we see that in choosing beam splitter designs we should stay away from configurations which manifest the particle nature of the atoms, and the interactions and confinement potentials should let the wave nature (or momentum eigenstate) of the atoms to be manifest, in order to preserve coherence and thus permit phase-maintaining interferometry. In particular we should avoid abrupt discontinuity junctions of size comparable to atoms' de Broglie wavelength, and should rather use finer periodic beam splitting structures such as microfabricated gratings or optical standing waves such as used in free-space atom beam splitters, or else use time-varying global potential such as in the MIT Shin et al.[11] experiment to split the atom waves or BECs. Laser cooling in principle should help increase atoms' coherent length and improve the contrast of interferometry experiments, but the increase in coherent length due to laser cooling is insufficient to make the forking type of atom beam splitter to work since even the BEC's de Broglie wavelength is only on the order of a micron, instead of several meters as in the optical laser.

5. HYBRID ATOM INTERFEROMETER CONFIGURATION POSSIBILITIES

Since the chip-based atom interferometr design does have the prospect of miniaturization at least in the case of the laser-cooling and trapping configurations[27,28] , one would not want to entirely give up on this approach even if the current generation of beam splitter designs envisioned for the chip environment proved to be frustrated. Hybrid design based on both the free-space and beam-waveguide techniques is one way to take advantage of both the small-package aspect of the chip-based design, aided by laser cooling, and the successful heritage of the free space design, with its flexibility to the variation of the pathlengths, and free of the perturbations introduced by the guiding potentials of the magnetic-chip-based or optical-dipole-potential-based atom interferometry structures. Currently, the free-space atom interferometry is the only one which has demonstrated practical usefulness in serving as inertial and field sensors, and achieving a sensitivity (when performing inertial sensing) comparable to that of optical sensors, and has the added advantage of being able to sense electric and magnetic fields, as well as gravitational fields and their gradients. The free-space beam splitters were also the only ones as of now permitting the use of both BECs and cold or thermal atoms.

Here we outline several possibilities for the hybrid design:

1. Use the chip-based setup to perform laser-cooling, then launch the cooled atoms into a free-space propagation path, and used free-space techniques such as material gratings, optical lattices and optical pulses to do the beam splitting and beam combination, then detect the atom fringes using either free-space or chip-based detection techniques.

2. Depending on the spread of the atom wave package, the "free space" propagation section of the configuration could be just a segment of space suspended above a connected substrate/packaging structure, so that the entire interferometer configuration could still maintain the characteristics of the "integrated atom optics" design. Figure 12 shows the schematic of such a hybrid design for a separated-path atom interferometer capable of inertial sensing and field sensing, where the laser-cooling and atom trapping part of the setup consists of the now-standard chip-based magneto-optical trap (MOT), which launches the cold atoms into a free-space segment of the propagation region. The collimation, beam splitting and beam combining optics makes use of the free-space technique utilizing laser standing wave gratings, themselves generated using the chip-based VCSEL (Vertical Cavity Surface Emitting Laser) technology. The detector and its associated circuits could also be integrated into the same package.

3. Though the recent chip-based atom beam splitting experiments involving the traveling waves have invariably failed, the limited success of experiments using the time-varying dipole potential[11] or laser standing wave pulses[12] to split a stationary BEC, as well as the success of the various BEC dividing experiments in the optical lattices[18,29] indicate that there is promise in configurations keeping the BEC ensemble whole, but varying the confining potentials with time in a fashion so that the global boundary conditions maintain the coherence of the BEC before and after the atom splitting. These types of configurations, however, even when successful, will only be of more limited use (e.g. in measuring certain local field gradient) compared to the versatilities of the classical atom interferometers where two traveling atom beams enclosing a fixed area are interfered. Plus, their usefulness in cold atom ensembles other than the BECs is yet to be demonstrated. In fact, it appears likely that the BEC-based sensors and the cold/thermal atom based sensors may require different propagation and beam-splitting configurations, in that the atoms may prefer the free-space type of traveling-wave configuration and grating type of beam splitters, whereas the BECs may prefer to start out nearly stationary, and be split and recombined by the time-dependent global splitting potentials.

6. CONCLUSIONS

In this report we have summarized the different atom interferometry configurations and beam splitter designs with the objective to guide the selection of a particular configuration and design to suit each type of applications. One of the conclusions resulting from this survey is that the best choice of atom interferometer configuration depends on the particular application under concern, and thus is not universal. We have also learned from a new heuristic model of the quantum measurement process first presented in this report that the current generation of forking type of guided-atom beam splitter design is not likely to be successful as a matter of principle, which may account for the persistent difficulty in implementing this type of beam splitters by the worldwide community, and the recent shift of direction in the beam splitter design from that of the discontinuous forking type to various ways of utilizing global splitting potentials.

Due to the experimental nature and the known limitations of the current guided-atom beam splitter prototype models, which permit only limited range of potential applications even if their coherent time and coherent separation distance can be significantly improved, new advances in the miniaturization of atom interferometers with practical applications will likely result from a hybrid design integrating the characteristics of both the current generation free-space atom interferometers, and the current generation laser-cooling and trapping techniques in the chip-based environment. One of the corollary of this conclusion is that further research into free-space atom interferometry, which has been overwhelmed in the recent years by the chip-based study effort in most of the worldwide institutions (with the exception of the Kasevich group at Stanford, which continued with the free-space effort), would prove to be a worthwhile endeavor in terms of producing atom interferometric sensors with practical applications, and also in terms of pushing the technological limit of the sensitivities of atom interferometers from the current level of being comparable to light-based sensors, to their ultimate limits set by the fundamental physics, which is 10-13 orders of magnitude the sensitivity of their light-based counterparts. Further research into chip-based technologies should also continue since it provides compact cold atom sources which will be useful in a hybrid-design atom interferometer, and the future for stand-alone chip-based devices such as chip-based atomic clocks or local field gradient sensors is still open despite the limitations of the guiding configuration on sensors of more conventional applications, i.e., inertial sensors and large-area field sensors.

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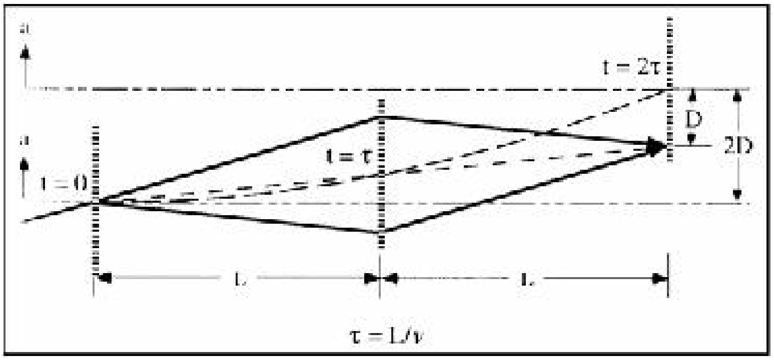

Figure 1. Free-Space Atom Interferometer for Inertial Sensing (Schmiedmayer et al.[14]).

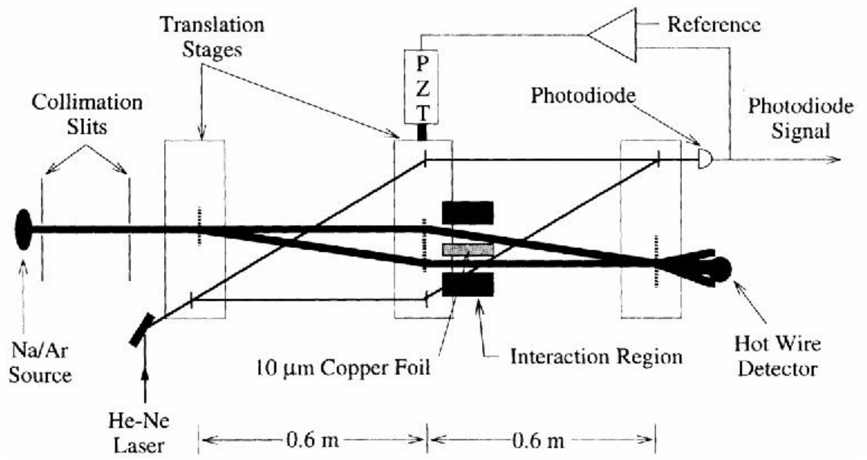

Figure 2. Free-Space Mach_Zehnder Interferometer at MIT (Schmiedmayer et al.[14]).

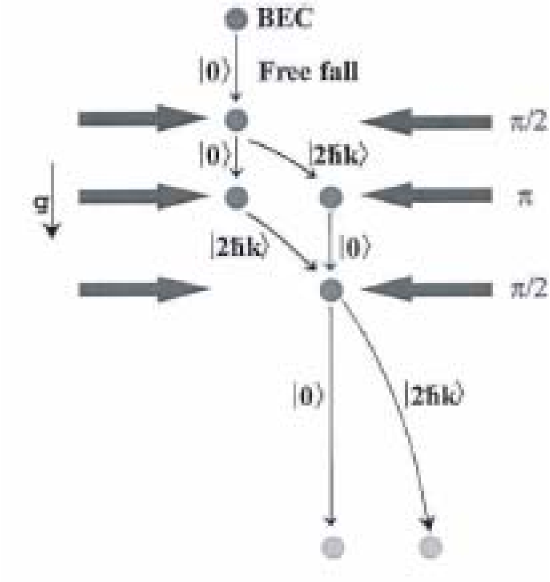

Figure 3. Free-Space Atom Interferometer Using Raman Pulses. This Particular Configuration Uses Two Counter-Propagating Laser Beams, and Can Be Used to Measure the Earth Gravity Gradient (Torii et al. [17]).

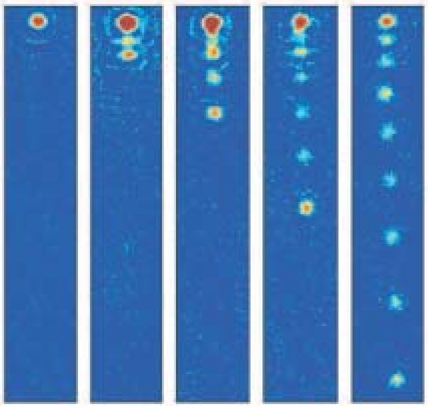

Figure 4. Interference of Cold Atoms Confined in Optical Lattices and Released and Accelerated by Earth's Gravity Which Leads to the Interference of the Atoms from Different Lattice Sites after Being Released (Anderson and Kasevich[18]).

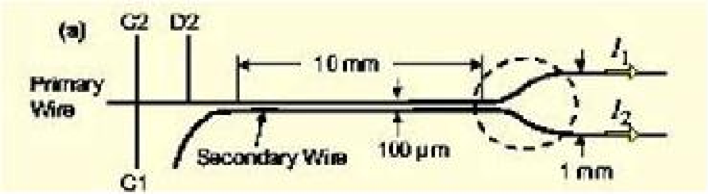

Figure 5. JILA Atom Chip Beam Splitter Design (Schwindt[9]).

Figure 6. JILA Atom Chip Beam Response to Thermal Atoms (Schwindt[9]).

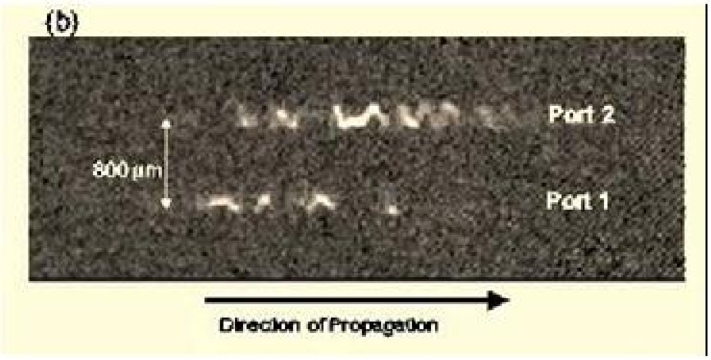

Figure 7. JILA Atom Chip Beam Splitter Response to BEC (Schwindt[9]).

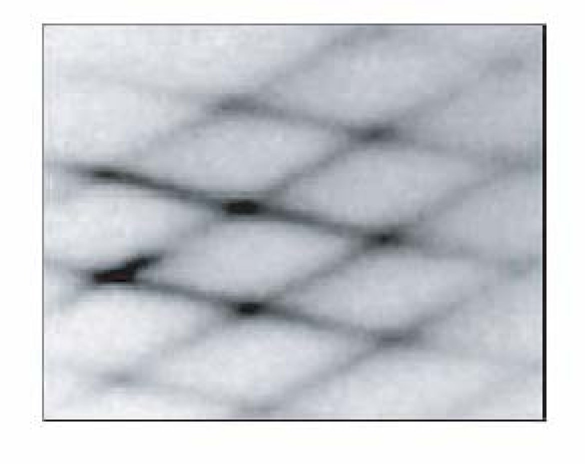

Figure 8. The Optical Waveguide Beam Splitting Experiment by the Hanover Group (Dumke et al.[8]).

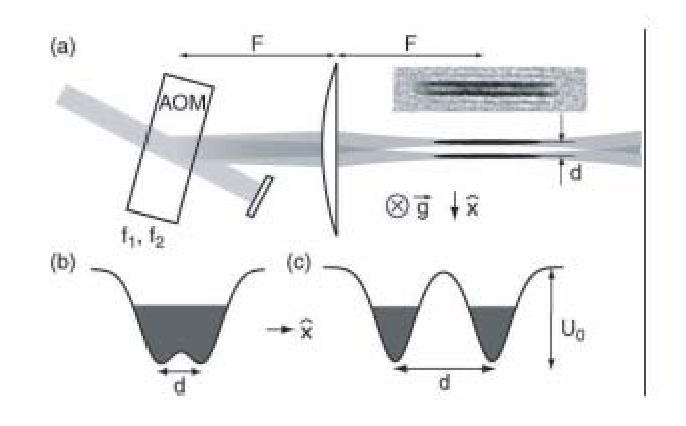

Figure 9. Experimental Setup to Create the Dipole Potential of the Recent MIT Experiment (Shin et al.[11]).

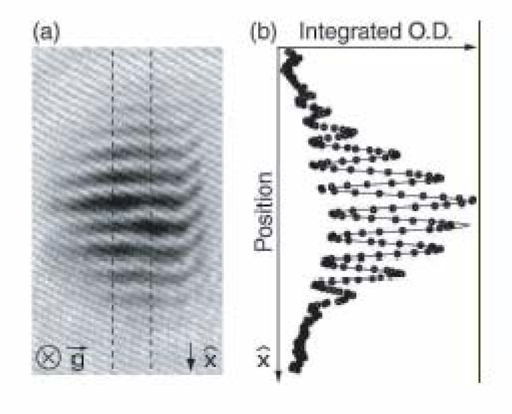

Figure 10. Interference Fringes Observed When the Separation of the Two Peaks of the Dipole Potential Are Reduced so that the Two Separated BEC Clumps are Brought to Interfere with Each Other (Shin et al.[11]).

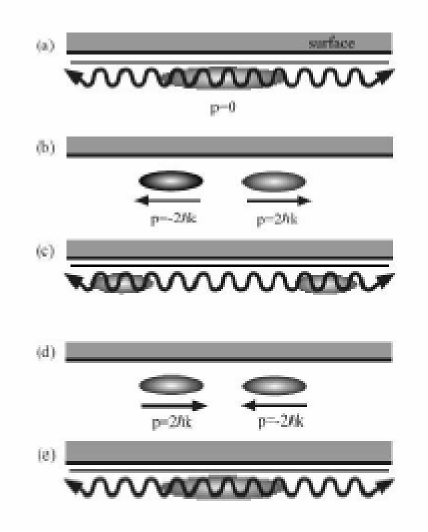

Figure 11. BEC Splitting and Recombining in the Atom Chip Environment Using Optical Standing Wave Pulses (Wang et al.[12])

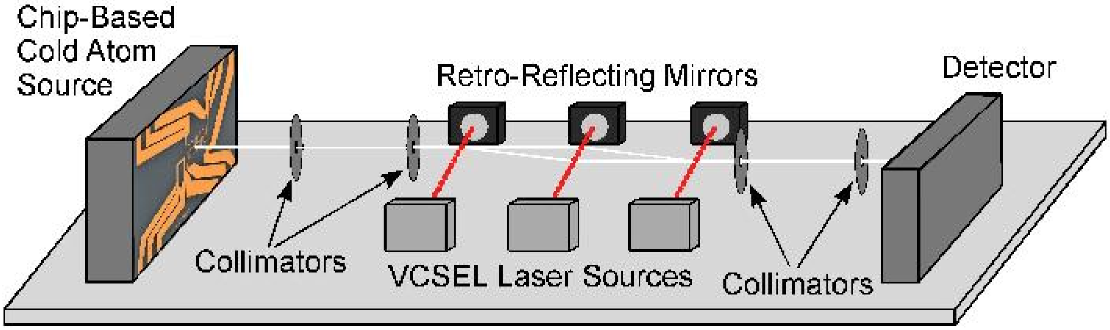

Figure 12: Schematic of a Hybrid Design Atom Interferometer Using both the Free-Space and Chip-Based Technologies. Only the Atom Beam Paths Which Pass Through All the Collimators Are Shown.