EXPERIMENTAL METAPHYSICS

Quantum Mechanical Studies for Abner Shimony
Volume One

Edited by

ROBERT S. COHEN
Boston University
Center for Philosophy and History of Science

MICHAEL HORNE
Stonehill College
Department of Physics

and

JOHN STACHEL
Boston University
Center for Einstein Studies and Department of Physics

KLUWER ACADEMIC PUBLISHERS 1997
DORDRECHT / BOSTON / LONDON

TABLE OF CONTENTS

JOHN F. CLAUSER

DE BROGLIE-WAVE INTERFERENCE OF SMALL ROCKS AND LIVE VIRUSES

INTRODUCTORY ABSTRACT

This paper discusses a new form of interferometry that we have developed and call Generalized Talbot–Lau (GTL) interferometry. The Talbot effect is a wave-interference effect that occurs near a diffraction grating in the region where Fraunhofer diffraction orders overlap and interfere. It is a pure Frasnel diffraction effect that creates a diffraction pattern consisting of a near phase and amplitude self-image of the grating, or multiply overlapped (aliased) copies thereof. Our generalization of this effect provides an analytic formulation of its self-imaging properties in the domain of finite (N-period) gratings. We have further integrated the generalized Talbot effect with the related Lau effect to allow construction of lens-free GTL interferometers. These consist simply of a sequence of three (or more) very wide transmission gratings, illuminated by uncollimated spatially incoherent waves. When used with vacuum slit gratings, such an arrangement may be applied to (non-penetrating) de Broglie waves. We have thus used this arrangement to demonstrate de Broglie wave interference for whole atoms. The unique scaling of the required grating periods with wavelength will allow, in the near future, heretofore impossible demonstrations of de Broglie wave interference, with very high mass species, such as very small rocks and even live viruses. Such an experiment, in turn, can provide severe constraints for various theories recently proposed to explain wave-function collapse.

"PROFESSOR, I SEE DOTS BEFORE MY EYES!"

Young's two-slit experiment has a special role in quantum mechanics, and embodies some of its mystery. Schrödinger's equation predicts that when a beam of de Broglie waves is projected through two slits onto a screen, the continuous complex valued waves described by this equation will form a continuous diffraction pattern on the screen, as will waves described by any linear classical wave equation. However, when such an experiment is performed with de Broglie waves, instead of a continuous pattern, a quasi-random set of dots is formed on the screen. Curiously, the density of dots is proportional to the predicted intensity of the waves. None the less, an experiment finds a bunch of dots and *not* a continuous pattern!

An honest but naïve undergraduate performing such an experiment wonders why the experimental observation of dots doesn't agree with Schrödinger's prediction for a continuous pattern. An honest professor grading the lab report would mark the student wrong if he/she claimed agreement with Schrödinger's prediction. The rest of us, however, being raised in an era of national Constitutions that don't exactly agree with associated legislation, accept the Supreme Court's

R.S. Cohen, et al. (eds.), Experimental Metaphysics, 1–11.

''interpretation'' that the emperor really does have some clothes on, and mark the student correct when he/she proclaims perfect agreement, and incorrect if he/she does not. Nevertheless some of us (secretly or not) still find it mysterious that there is an evident discrepancy between Schrödinger's wave-theory and observation.

David Bohm (1952) produced a tentative theory that had both waves and propagating dots. It explains this quasi-random distribution with great clarity. The dots simply ''surf'' on the waves and thereby are guided to the screen with the observed distribution. This mechanism is similar to one in plasma physics (a field to which Bohm also made significant contributions) called **Landau damping**. Following Bohm, however, John Bell, Abner Shimony and friends showed that Bohm's theory, indeed any theory that explains the dots as the impacts of trajectories of localized particles, raises very serious problems concerning our concept of space-time (see Clauser and Shimony, 1978). ''You mean it gets worse still?'', cries the bewildered student! One is now led away from the problem of understanding the dots to the far more perplexing problem of understanding non-local *quantum-entanglement*. None the less, Richard Feynman still claimed that the two-slit problem contains ''the only mystery''! ''You mean, if we explain the dots, we now have complete clarity?'' I wish it were as simple as Mr. Feynman contends Bohm's theory does, and we don't.

Most introductory textbooks on quantum mechanics provide a discussion of the orders of magnitude involved for quantum interference and argue that these are so large or so small that quantum interference effects do not appear for macroscopic objects. Hence, it is argued, quantum mechanics has no impact on ordinary, everyday experience. Hence, we should expect dots! ''Huh? Ordinary, everyday waves, such as those on a pond's surface, don't produce dots!'' Much of the force of these discussions intimidates the student, so that when it comes time to discuss the more paradoxical (or otherwise hard to grasp) provisions of quantum mechanics, he/she blindly accepts these provisions, assuming their explanation to be buried in this large order-of-magnitude dissimilarity. Basically, the ''order-of-magnitude intimidation'' method of argument points out that at very short wavelengths, Schrödinger-wave theory (indeed any wave theory) reduces to having the slits produce geometric shadow intensity patterns. Hence, probability arises naturally from a deterministic theory! ''Huh?'' Hence, there is no problem with finding dots instead of continuous waves, and the classical limit of point impacts of particles is obtained! ''Double huh?''

''You do not see the crystal-clear logic here? Let me continue the argument then.'' Everyday experience gained by throwing small rocks at a wall containing two open windows indicates that (1) a rock can go through only one window at a time, and (2) there are no evident quantum interference effects observed on the other side of the wall once the rocks pass through. Instead, the distribution of rock impacts formed on a second wall positioned behind the first appears as a simple geometric shadow pattern of the two windows. ''Gee!'' says the student. ''That seems reasonable. In this limit continuous waves and rock impacts are both distributed in a geometric shadow pattern. Given enough rocks, you no longer notice the dots. Go on.'' On the other hand, when a similar experiment is performed with a long de Broglie wavelength species (other than rocks) and smaller more closely spaced windows, then whether or not experience (1) occurs may well be impossible to determine, and experience (2) no longer obtains. Hence, we must see dots! "Oh, yeah, now I understand clearly. Like hell, I do!"

An honest student may then ask if we really know how to solve Schrödinger's equation, or indeed solve any wave equation for this simple two-slit problem. "Of course we do! Don't we?" Given the many discussions offered on the Young's interference experiment, it is highly curious that even the one-slit problem in quantum theory has not been provided with a rigorous solution. However, this problem seems to be an important one that is right at the heart of both the measurement problem and the conceptual foundations of quantum theory. It is noteworthy that Born and Wolf (1987) offer a chapter on "Rigorous diffraction theory" that presents calculations of the approximate wave amplitude everywhere for the half-slit diffraction problem (diffraction by an infinitely thin half-plane) for classical electromagnetic waves. However, to my knowledge, even the half-slit problem has not been solved with a similar degree of rigor for de Broglie waves, especially in a manner that gets to the crux of the problem by including a detailed interaction of the slit-imposed particle-absorbing boundary conditions for de Broglie waves.

More commonly, a pair of slits are taken to be a very simple von Neumann measurement device. The similarity to a von Neumann device is enhanced further if the slits are made from film such that particles not passing through the slits are detected thereon. Indeed, with absorbing slits (inelastic boundaries), the most commonly applied (non-rigorous) solutions of this problem, used by both classical and quantum mechanical treatments of the problem, are those of standard Huygens–Fresnel–Kirchoff diffraction theory, in which the wave amplitude simply collapses at the boundary. The use of this solution then sidesteps many of the issues regarding the unresolved debate between Kirchoff, Rayleigh and Sommerfeld as to whether or not self-consistent boundary conditions are being applied, even in the domain of classical waves (see e.g. Goodman, 1968; Peterson and Kasper, 1972). The fact that experimental observations of wave intensity made in the very far field appear to agree with these solutions is then used to justify the sledge-hammer approach used in their derivation.

"Does our inability to solve the wave equation relate to the problem with our finding dots? Of course not!" "Well then, is quantum theory maybe wrong? Is that why we see dots?" "Unthinkable! Don't you see the emperor's fine clothes? Mr. von Neumann points out that there are really two different processes at work here – Schrödinger (unitary) evolution and wave-function reduction or collapse. That's why we see dots! Now do you understand?" "Gee, how does this collapse-thing work? Is there a more general equation than Mr. Schrödinger's that explains both processes in a unified way? Given this entanglement stuff, however, it is hard to see how this can be a real physical process. Maybe if we can just understand the dots, as Mr. Feynman proposes, then the entanglement stuff will go away." "No problem, just concentrate on the emperor's fine clothes! It's just a matter of you young political radicals accepting a proper *interpretation* of our national

Constitution (i.e. that by Max Born)! If you believe firmly enough in this *interpretation* (and wave the flag enough), you probably won't even need this wave-function collapse thing either.''

POSSIBLE EXPLANATIONS FOR THE ''DOTS''

Bohm and Bub (1966) first suggested ''corrections'' to Schrödinger's evolution that provide a physical process for wave-function collapse. It is noteworthy that since their early effort at least six conceptually similar theories have been proposed. Two of these are discussed at this Symposium – one by Philip Pearle (see also Pearle and Squires, 1994), and one by Roger Penrose (see also Penrose, 1994). Others include one by Diósi (1987, 1989) as an extension of the Ghirardi–Rhimini–Weber theory, the Ghirardi–Rhimini–Weber (1986, 1987) theory itself, one by Hawking (1975), and one by Ellis *et al.* (1984). All of these theories contain free parameters that specify characteristic collapse times and distances, as well as additional terms beyond those in Schrödinger's equation. All then provide for spontaneous localizations in the propagation of de Broglie waves that explain the dots, and all provide an experimentally accessible breakdown of Schrödinger evolution.

Each theory attacks the problem of dot formation in the two-slit experiment from a different perspective. As I am not an expert on these theories, I will leave a calculation of their specific predictions to their authors. However, I do note that all of these theories appear to offer a breakdown of quantum interference for the two-slit experiment when very massive (and/or finite-sized) very short de Broglie wavelength objects are used in this experiment. Correspondingly, they all provide for a disappearance of quantum interference effects somewhere in the domain between that for large rocks and that for elementary particles such as electrons.

TESTING THESE EXPLANATIONS WITH ROCKS IN A TWO-SLIT (OR *N*-SLIT) EXPERIMENT

Curiously, although the above theories start from quite different premises, many appear to provide a breakdown at about the same parameter values. This coincidence is probably because the free parameters have been adjusted for the breakdown to occur in an experimentally inaccessible ''theorist's safe haven'' parameter range. A Young's two-slit experiment performed with matter-waves for very massive particles (rocks) then seems to be a natural arena for probing the classical–quantum boundary for a possible breakdown, and for testing (or at least constraining) the above theories. The breakdown hopefully appears before the point where the rocks become sufficiently large that they will no longer fit through the slits. If the rocks don't fit through, then the two-slit experiment becomes inapplicable as a testing ground, and one must attack, head-on, the unsolved problems in diffraction theory mentioned above.

A Bodacious[1] experimentalist, when contemplating the associated orders of magnitude for rocks, rather than viewing them as intimidating, finds them an interesting challenge. Given significant advances in the state-of-the-art of experimental physics, one wonders if very large quantum objects, such as very small rocks, can be made to demonstrate de Broglie-wave interference, whereupon one may significantly narrow the parameter regime available for theorists' speculation. This paper proposes such an experiment. While the parameters available from the proposed experiment may not yet reach the critical values needed to refute all of, or even some of, the above theories, they may at least make the authors slightly nervous.

GTL INTERFEROMETRY

At our laboratory in the past few years, we have helped advance the state of the art for the Young's *N*-slit experiment to a point where we have performed it with large "composite" particles such as whole potassium atoms (Clauser and Li, 1994a, 1994b). We do so with a method we have developed and call Generalized Talbot–Lau (GTL) interferometry. The detailed theory behind this scheme is given by Clauser and Reinsch (CR) (1992) (see also Clauser and Li, 1997). It is based on a unique form of interference that is intimately associated with Fresnel diffraction. This effect occurs in the near field region behind a diffraction grating where the various Fraunhofer diffraction orders overlap and interfere. Fresnel diffraction is essential for its explanation, since the effect depends on the distance between the illuminating source for the diffraction and the diffraction grating, while the Fraunhofer diffraction order positions do not. It was originally discover by Talbot (1836) (see also Rayleigh, 1881) in the optical domain using lenses and gratings, and is called the Talbot effect. The diffraction pattern formed by the interfering orders consists of multiply "aliased" near self-images of the grating's periodic complex amplitude transmission function. One special limiting case among the many possible image patterns formed is the geometric shadow pattern (see below).

The layout for a GTL interferometer is shown in Figure 1. It consists simply of a set of three very wide diffraction gratings Gs, Gd, and Gm, in sequence, wherein the notation indicates their specific respective function as source, diffraction, and mask gratings. For our purposes here, each such grating is simply a thin sheet of solid material with parallel slits cut through. The associated slit periods are then a_s, a_d, and a_m, respectively, and the inter-grating spacings are R_1 and R_2. These gratings are illuminated by scalar waves of basically any kind (including de Broglie waves), with the one restriction that they be quasi-monochromatic. The illuminating source may be extended, uncollimated, and spatially incoherent. Since there is no upper limit to the gratings' widths, W_{Gs} and W_{Gm}, a GTL interferometer has a very high throughput, yet is still capable of producing very high contrast fringes. For interferometry with slow atoms, where available source brightness is considerably less than that for fast atoms, it is particularly useful.

How does it work? In a GTL interferometer each point within each slit of Gs acts as an independent point source. For each such source, diffraction grating Gd produces strongly overlapped Fraunhofer diffraction orders on the face of Gm. However, in this overlap region Fresnel diffraction applies, and the various orders coherently superpose to create a form of wave interference – unique to Fresnel

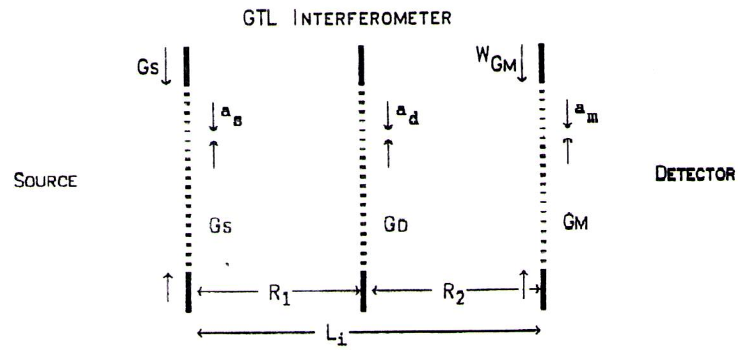

Figure 1. Layout for a GTL interferometer.

diffraction – called the Talbot effect. The interference produces a non-sinusoidal standing de Broglie wave (interference fringe) on the face of Gm, thereby allowing Gm to act as a mask, so that the fringe pattern's presence may be detected by laterally scanning a grating's position and observing an associated variation induced in the transmitted current. For sufficiently narrow Gm slits the finite slit width only slightly washes out the fringes. Thus, while the gratings still physically separate the various interfering paths within the beam's envelope, that envelope itself does not separate. Interfering paths within the envelope consist topologically of many sets of nested diamonds, starting in a given slit on Gs, passing through the various Gd slits and terminating at a point on Gm, where they interfere.

Now if Gs is suitably periodic, each Gs slit produces essentially the same standing wave as that produced by other Gs slits. The contribution by all Gs slits then add to the intensity without deteriorating the fringe visibility. Again, for sufficiently narrow Gs slits the finite slit widths further wash out the visibility only slightly. This incoherent addition of Talbot fringe patterns is called the Lau effect (1948). It is noteworthy that while the usual demonstrations of the optical Talbot and Lau effects require the presence of one or more lenses, our generalization of these effects allows a lens-free system.

The arrangement has very high grating-misalignment tolerance. Since no collimation is needed, the formation of the standing wave is independent of the source area and input *k*-vector direction; hence, neither coma nor spherical aberration occurs. The price paid for the high angular acceptance is, however, significant chromatic aberration. The standing wave formed at Gm is strongly dependent on illumination wavelength and is *not* a simple geometric shadow effect, but a *true* interference effect. Depending on illumination wavelength, the standing-wave period appears at various different harmonics of the shadow period. Actually, this chromatic aberration manifests itself as a resonant chromatic selectivity that proves to be desirable in many instances, and can even act as a de Broglie-wave interference filter (Clauser and Li, 1994b).

Grating Gd is assumed to contain N slits. The basic scaling for interference in this arrangement depends on three important parameters – the "reduced length", ρ, defined as:

$$\rho \equiv \frac{R_1 R_2}{R_1 + R_2} \tag{1}$$

the geometric shadow magnification, M, defined as:

$$M \equiv \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} = \frac{R_2}{\rho} \tag{2}$$

and the quantity:

$$\lambda_{TR} \equiv a_d^2/\rho \tag{3}$$

that we have named the Talbot–Rayleigh "wavelength". The CR (1992) analysis shows that the basic requirement for a "fringe" resonance to occur (whereupon self-imaging occurs) is given by:

$$\frac{\lambda_{TR}}{\lambda} = \frac{a_d^2}{\lambda\rho} = \frac{m}{n} + \varepsilon \tag{4}$$

where m and n are small integers and ε is small. This relation (with $\varepsilon = 0$) was first discovered by Winthrop and Worthington (1965) and by Gori (1979), and generalized by CR to allow a small tuning error ε. These integers are what we call "resonance indices". Effectively, they are quantum numbers for this geometry. Equation (4) then represents a *fundamental constraint* for the generalized (finite-N) Talbot effect to occur. Even minor changes to the geometry or wavelength will call for a different set of m, n, and ε, and significantly affect the image pattern formed.

Consider the images formed on the Gm plane by a point source located on the Gs plane. Cowley and Moodie (CM) (1957) found that they are of two different kinds, which they named "Fourier images" and "Fresnel images". The analysis and experiments by CM explained the Fourier images for infinite gratings, but left Fresnel images as quite mysterious. The analysis by CR with finite gratings first fully explained the origins of the formation of Fresnel images. Fourier fringes are formed on the image plane for $m = 1$ and integer values of $n \geq 1$. The terms "fringe" and "image" may be applied to the pattern formed on the Gm plane only loosely, as the pattern's shape is, in general, non-sinusoidal, but is not an image either in the usual sense. Indeed, the pattern's amplitude is a magnified (by M) near replica of the complex grating amplitude transmission function itself. For a finite number of slits, $N < \infty$, the pattern is a filtered (slightly rounded) amplitude self-image, with the associated filtering given by CR's (1992) equations (25)–(27). In the $N \to \infty$, $\varepsilon = 0$ limit, the self-image is an exact magnified replica. For $N < \infty$, the filtered self-image has a finite envelope (produced via: CR, 1992: equation (25)) that is comparable to the grating's magnified finite shadow width. For finite N approximate self-imaging persists for a finite range of $\varepsilon \neq 0$, limited by the inequality, $|\varepsilon| < 2 / (n\ N)$.

Fresnel fringes are formed on the Gm plane for integer values, $m > 1$ and $n \geq 1$. Clauser and Reinsch (1992) generalize the Gori (1979) and CM (1957) results to cover general complex gratings so as to show that the pattern now consists of m copies (aliases) of the "filtered" $m = 1$ (Fourier) amplitudes self-image per geometric shadow period, with the associated complex amplitudes all added together. The result is a periodic pattern with period Ma_d/m. Thus, we call the resonance index m the "alias multiplicity". Because of this addition, the resulting added set of images is no longer itself a self-image of the original grating, although each of the added components is such a self-image. Correspondingly, for $m > 1$ the summed pattern for a binary grating does not preserve the original grating's slit-width to period-width ratio. The $m = 1$ case is obviously consistent with the $m > 1$ case, as the Fourier image case represents the Fresnel image case wherein only one copy, the filtered self-image itself, is present. Correspondingly, other features of the $m = 1$ case discussed above, also persist in the $m > 1$ case.

Another curious feature of the generalized (finite N) Talbot effect is its close connection with number theory. Whenever the product $m \times n$ is odd (whether or not N is finite), then the whole pattern is shifted laterally (relative to the position of the geometric shadow pattern) by half a shadow (magnified) period. When the added components of a Fresnel image overlap, their added amplitudes interfere, so that the integer fraction m/n is always reduced to lowest terms. Finally, the Clauser–Reinsch formulae (25)–(27) apply exactly only when n is an integer factor of N. This later fact then allows a Young's N-slit interferometer to act as an analog computer that can find the integer factors of N (Clauser and Dowling, 1996).

The analysis by CR also clarifies the formation of periodic geometric shadows. The condition $n = 0$, $\varepsilon = 0$, holds when the wavelength λ exactly vanishes, i.e. the $\lambda \to 0$ ($n = 0$, $\varepsilon \to 0$) limit is the geometric shadow limit. Clauser and Reinsch (1992) show that for binary gratings (opaque gratings with slits of width σ_d) and small but finite λ, the mth Fourier coefficient of the shadow pattern (dominantly contributed by the mth Fresnel image) vanishes abruptly at $\lambda / \lambda_{TR} = \sigma_d / (m\, a_d)$, with the coefficient for the fundamental ($m = 1$) component correspondingly persisting to longest wavelength, and itself then abruptly vanishing. This latter sharp boundary may then be viewed (loosely, via the Constitutional *interpretation* approach method only) as a sharp boundary between wave and particle behavior. Actually, it demonstrates an abrupt onset of multi-slit interference.

GTL INTERFEROMETRY APPLIED TO SMALL ROCKS (OR LIVE VIRUSES)

While we have used GTL interferometry to do what amounts to the Young's N-slit de Broglie-wave experiment with large atoms (Clauser and Li, 1994a), the wavelength scale used for atoms does not even approach the limits for GTL interferometry. Suppose one desires to do this experiment with a very massive particle species. As per de Broglie's famous relation, such a species with mass m and velocity v will have a de Broglie wavelength given by $\lambda = \lambda_{dB} = h/(mv)$. Consider the arrangement for Figure 1 with $a_s = a_m = 2a_d$, where we specify a convenient overall interferometer length of $R_1 + R_2 = 3$ m. Unambiguous wave interference, that is clearly *not* a simple geometric shadow effect, can be demonstrated using the $n = 1$, $m = 2$ resonance, through the fact that the image

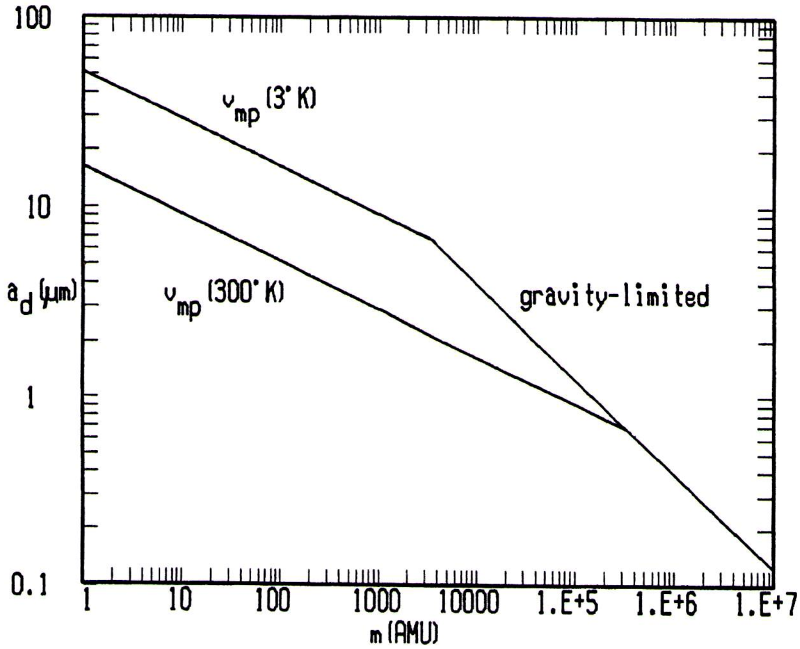

Figure 2. Required Gd grating period, a_d, as a function of species atomic mass number for a 3 m long $n = 1$, $m = 2$ GTL interferometer.

period is now one-half of that of the geometric-shadow period. Hence, if any grating is translated laterally, the transmitted *rock* flux will be observed to vary at twice the frequency to be expected for a simple geometric shadow being formed on the Gm plane, and being masked by the Gm grating.

How can we do this with a very large mass (short λ_{dB}) species? A unique feature of the above formulae is that for GTL interferometry the required Gd grating period a_d that is needed to create a given n, m resonance scales only as $\lambda_{dB}{}^{1/2}$. For thermal rocks of mass m, whose velocity then scales as $(kT/m)^{1/2}$, the grating period thus scales only as $m^{-1/4}$. Figure 2 plots this period as a function of species atomic mass number for a 3 m long ($\rho = 0.75$ m) interferometer. The two lines on the left are for the most probable particle velocity for thermal particles at 300°K and 3°K, respectively, while the right side's limiting line is for freely falling particles gravitationally accelerating in the 3 m interferometer length. (GTL interferometry in the presence of a gravitational field is discussed by Clauser and Li, 1996.)

What about the finite coherence length of the rocks? Presumably, there is no coherence among the rocks, so that, as with atoms, the rocks' translational velocity spread determines their effective "coherence length". Correspondingly, the associated determinant of fringe visibility (as with atoms) is actually the velocity spread of the rocks within the beam, relative to the width of the associated interferometer resonance. If the rocks are "cold" enough so that their velocity (and λ_{dB}) distribution fits fully within the associated interferometer resonance (assumed

$n = 1$, $m = 2$ for the calculation), then a high visibility $m = 2$ pattern will be formed at twice the spatial frequency of the geometric shadow pattern. For initially "cold" slow rocks, whose velocity quickly becomes dominated by gravitational free-fall, then the "gravitational pseudo-cooling", sometimes also called dynamic velocity compression (see Clauser and Li, 1996: sect. XV) is so strong, and the $n = 1$, $m = 2$ resonance is so broad, that this condition is very easily satisfied. On the other hand, if the rocks are "hot", a thermal velocity spread centered on the $m = 2$ resonance will still show a strong second harmonic component, although other harmonic content will be present also. In either case, wave interference may be unambiguously demonstrated.

Actually, "coherence length" is not a particularly useful concept for gravity-dominated motion. Indeed, we run into a similar "paradox" when considering the same problem for our current rubidium experiment. Gravitational pseudo-cooling is such an effective process that a naïve calculation of coherence length for the falling rubidium atoms in our current experiment shows that the coherence length of ultra-cold atoms dropped from a MOT (magneto-optic trap) expands with time and quickly becomes longer than its accumulated free-fall distance. Does it then "bounce back" and have a finite amplitude for re-appearing at the source? The paradox is resolved by integrating the Heisenberg equations of motion for a wave packet in free fall. It doesn't.

CONCLUSION

Using currently available electron-beam lithography and microfabrication techniques allows fabrication of free-standing vacuum-slit gratings, with slit periods as small as 0.05 μm. Thus, one can see from Figure 2 that GTL de Broglie-wave interferometry with very massive particles (containing, say, 10^8 nucleons), such as very large atomic clusters (i.e. very small rocks) or even small live viruses, may be achievable in the near future. I will leave the remaining question as to whether or not these limits put the above theories in an awkward position as a question posed to their authors.

Dept. of Physics
University of California, Berkeley

NOTE

[1] Bodacious is a very fast Farr-40 1-ton.

REFERENCES

Bohm, D., 1952, *Phys. Rev.* **85**, 166, 180.
Bohm, D. and Bub, J., 1966, *Rev. Mod. Phys.* **38**, 453, 470.
Born, M. and Wolf, E., 1987, *Principles of Optics*, Oxford, Pergamon.
Clauser, J.F. and Dowling, J.P., 1996, *Phys. Rev. A* **53**, 4587.
Clauser, J.F. and Li, S., 1994a, *Phys. Rev. A* **49**, R2213.

Clauser, J.F. and Li, S., 1994b, *Phys. Rev. A* **50**, 2430.
Clauser, J.F. and Li, S., 1997, in Berman, P. (ed.), *Atom Interferometry*, Academic Press, San Diego.
Clauser, J.F. and Reinsch, M.W. (CR), 1992, *Appl. Phys. B* **54**, 380.
Clauser, J.F. and Shimony, A., 1978, *Rep. Prog. Phys.* **41**, 1881.
Cowley, J.M. and Moodie, A.F. (CM), 1957, *Proc. Phys. Soc. B* **70**, 486, 497, 505.
Diósi, L., 1987, *Phys. Lett. A* **120**, 377.
Diósi, L., 1989, *Phys. Rev. A* **40**, 1165.
Ellis J. *et al.*, 1984, *Nucl. Phys.* **421**, 381.
Ghirardi, G.C., Rhimini, A. and Weber T., 1986, *Phys. Rev. D* **34**, 470.
Ghirardi, G.C., Rhimini A. and Weber T., 1987, *Phys. Rev. D* **36**, 3287; see also Benatti, F., Ghirardi, G.C., Rhimini, A. and Weber, T. *Nuovo Cimento B* (1987) **100**, 27.
Goodman, J.W., 1968, *Introduction to Fourier Optics*, New York, McGraw-Hill, Chapt. 3.
Gori, F., 1979, *Optics Commun.* **31**, 4.
Hawking, S., 1975, *Commun. Math. Phys.* **43**, 199; see also Wald, R.M., 1975, **45**, 9.
Lau E., 1948, *Ann. Phys.* **6**, 417.
Pearle, P. and Squires, E., 1994, *Phys. Rev. Lett.* **73**, 1.
Penrose R., 1994, *Non-locality and Objectivity in Quantum State Reduction*, preprint.
Peterson, S.D. and Kasper, J.E., 1992, *Amer. J. Phys.* **40**, 1274.
Baron (Lord) Rayleigh, 1881, *Phil. Mag.* **11**, 196.
Talbot, H., 1836, *Phil. Mag.* **9**, 401.
Winthrop, J.T. and Worthington, C.R., 1965, *J. Opt. Soc. Amer.* **55**, 373.