

ULTRA-SENSITIVE INERTIAL SENSORS VIA  
NEUTRAL-ATOM INTERFEROMETRY

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Upon looking at the various colossal interferometers, *etc.*, discussed at this conference to test gravitational theory, one cannot avoid feeling that easier approaches exist. It is the purpose of this paper to suggest such. We propose to use low-velocity, neutral-atom matter waves in place of electromagnetic waves in sensitive inertial interferometer configurations. For applications we consider spacecraft experiments to sense a drag-free condition, to measure the Lense-Thirring precession, to measure the gravitomagnetic effect and/or the earth's geopotential (depending on altitude), and to detect long period gravitational waves. Also, we consider a terrestrial precision test of the equivalence principle on spin-polarized atoms, capable of detecting effects of the 5th force. While the ideas described herein are preliminary, the orders of magnitude are sufficiently tantalizing to warrant further study. Although existing proposed designs may be adequate for some of these experiments, the use of matter-wave interferometry offers reduced complexity and cost, and an absence of cryogenics.

Contrast Sagnac interferometer experiments to measure the rotation rate of the earth with a passive single-circuit ring cavity. The Michelson Gale experiment employed light and a ring area several times that of a soccer field, achieving less than one fringe sensitivity. A recent neutron interferometry experiment by Werner Staudenmann and Colella achieved many fringe sensitivity with an interferometer that fits in one's hand! As a simple rule of thumb, a matter-wave interferometer employing particles with velocity,  $v$ , gains sensitivity over an electromagnetic one with the same area by a factor of  $c/v$  for rotations and  $(c/v)^2$  for accelerations and gravity (Clauser 1987).

Although the spatial coherence of freely propagating atoms has been evident for some time, no one has yet built a separated beam interferometer. However, recently developed technology makes such a device feasible. For example, Sesko, Fan, and Wieman at JILA recently produced a beam of neutral cesium at 100 cm/sec with a single stage of laser cooling, and 15 cm/sec with a second stage. The temperature of the latter was 100  $\mu$ K. The deBroglie wavelengths for these atoms are 30 and 200  $\text{\AA}$ , respectively.

An illustrative configuration for such a device (shown in Figure 1) employs a sequence of three equally spaced planar gratings. One choice for such gratings is to employ diffraction by the spatially periodic electric field of a nearly resonant standing-wave laser beam (the atomic analog of the Kapitza-Dirac effect). An advantage of this method is that it allows the grating to be blazed to high order through choice of laser power and detuning. A second choice is diffraction by a microfabricated, submicron-spaced grid. A third choice (requiring a slightly different geometry) is Davidson-Germer diffractive reflection by available large perfect silicon crystal faces, in which each face is a nearly perfect lattice plane.

In Figure 1, a laser-cooled and decelerated atomic beam is coherently divided at the first grating, propagates along two paths consisting of the sides of a rhombus, being redirected at the middle grating. The paths then superpose and recombine on the last grating, whereupon interference occurs. If the last grating is tilted slightly with respect to the others, a highly magnified transverse fringe pattern will be formed across this grating. The necessary conditions for coherence and nonvanishing fringe visibility can be satisfied for suitable choices of grating and atomic beam parameters. Detection of the fringes can be done by imaging the fluorescent light produced at the final grating, or by measuring the profile of the transmitted beam by standard atomic beam techniques (e.g., ionization on hotwires).

If the interferometer described above is placed in a noninertial frame, it will exhibit a fringe shift. Let  $x$  be the distance between the outer two gradings,  $d$  ( $= \lambda_{\text{laser}}/2$ ) be the grating split spacing, and  $n$  and  $2n$  be the diffraction order at the end and middle gratings, respectively. Additionally, let  $\hat{o}$  be a unit vector perpendicular to the plane of the paths, and  $\hat{q}$  be a unit vector perpendicular to the line between the source and detector. Also, let  $\Omega$  be the rotation rate vector, and  $a$  be the sum of the acceleration and gravity vectors. The phase shift  $\delta$  (radians) that is due to rotation is given approximately by

$$\delta_{\text{gyro}} \approx \frac{2 \pi x^2 n (\Omega \cdot \hat{o})}{d v}$$

while that due to gravity is given by

$$\delta_{\text{grav.}} \approx \frac{\pi x^2 n (a \cdot \hat{q})}{d v^2} \cdot \left( \frac{m_g}{m_i} \right)$$

The gyroscopic and gravitational sensitivities depend differently on particle velocity. Thus, a pair of matter-wave interferometers employing different velocity atoms (e.g., *in-situ* along the same paths, but in different orders) can be used to determine both acceleration and rotation rate independently from a solution of the simultaneous equations. Six interferometers can sense all six components of the rotation rate and gravity plus acceleration vectors. With solid gratings (e.g., crystal faces or a microfabricated grid), if soft X-rays or UV also propagate *in-situ* along the same paths, then the resulting electromagnetic fringes will form a reference to allow servo-stabilization of the grating positions against their low frequency thermal motion or other mechanical flexure.

Consider a spacecraft experiment to measure the Lense-Thirring precession, similar to the Stanford Gyroscope Experiment, but with the superconducting sphere and cryo-system replaced by the interferometer of Figure 1. For a count rate  $R$ , a fractional fringe  $\pi/(R\tau)^{1/2}$  should be detectable, where  $\tau$  ( $=1/f$ ) is the integration time. For  $x \approx 1-10$  m,  $R = 10^6$  is realistic. If the atomic beam is focused (e.g., by additional lasers) this rate will be independent of  $x$ . Assume  $D = 0.5\mu$  (or  $\lambda_{\text{laser}} = 9521\text{\AA}$ ) with Cs at 1 m/sec. The sensitivity to rotations is then  $\Omega(\text{rad sec}^{-1} \text{H}^{-1/2}) = 7.8 \cdot 10^{-11} \times (\text{m})^{-2}$ . Thus an instrument with  $x = 100$  m and  $\tau \approx 1$  sec, or  $x = 10$  m and  $\tau \approx 10^4$  sec should sense  $\Omega$  (Lense-

Thirring)  $\approx 10^{-14}$ . This sensitivity will improve inversely with  $v$ . The same instrument can be used for drag-free sensing with an accelerometer sensitivity of a  $(\text{Gal Hz}^{-1/2}) \approx 1.6 \cdot 10^{-8} \times (\text{m})^{-2}$ . Although the interferometer can sense exact path equidistance (via the white fringe), spacecraft asymmetry may still cause a fixed imbalance. However, if the spacecraft rotates slowly about the star sensor axis ( $\perp o$ ,  $\perp q$ ), fringe variation synchronous with this rotation will constitute the usable signal and any fixed bias will cancel.

Gravitational gradients can be measured utilizing the same principles with a geometry in which the paths follow a two-loop structure (figure-eight with loops of equal area), shown in Figures 2a and 2b using Davidson-Germer diffraction by crystals). Because the circuits about the two loops are oppositely directed, the net area is zero. As a result, the interferometer will be insensitive to rotation, (except that it will also measure accelerational gradients such as those due to centrifugal acceleration). A gravitational field acting on one loop that is slightly different from that acting on the other, will yield a phase shift proportional to the difference. Thus, an interferometer with such geometry will measure gravitational gradients.

A spacecraft experiment with a gradiometer as per Figure 2a, with the same parameters as above, will have a sensitivity (for off-diagonal gradient components) of  $da/dx \approx 1.3 \cdot 10^{-2} x' (\text{m})^{-3} \text{ E Hz}^{-1/2}$ . Thus, a device with  $x' = 50 \text{ m}$  can detect a gravito-magnetic gradient of  $10^{-8} \text{ E}$  in  $\tau \approx 50 \text{ sec}$ .

Consider next the sensitivity of a Figure 2b gradiometer to long-period gravitational waves. Such a wave will deflect the matter waves asymmetrically within the interferometer and act like a gravity gradient. For  $n = 1$  the detectable strain,  $h$ , will be the fraction of a detectable fringe on the final grating divided by the extent  $x'$  of the device, *i.e.*,  $h \approx \eta d x'^{-1} (R\tau)^{-1/2}$ , independent of  $v$ . For a burst at  $10^{-5} \text{ Hz}$ , with  $\tau = 10^5$ ,  $d = 1 \text{ \AA}$ ,  $x = 100 \text{ m}$  and  $R = 10^6$ , the minimum detectable strain is then  $h \approx 10^{-17}$ .

As a final application, consider a terrestrial experiment in the Fig. 1 configuration, with microfabricated gratings, with a B field gradient everywhere (within the domain of the paths) parallel to  $g$ . An oscillating magnetic field, applied to the apparatus, will cause spin flips detectable by a loss of fringe visibility at resonance. Suppose one adjusts (and/or shims) the magnetic gradient for minimum resonance width. This will occur when the Zeeman energy everywhere cancels the gravitational potential energy. The resonance frequency will be proportional to the ratio of the gravitational to inertial mass of the atom. If two species simultaneously propagate (*e.g.*,  $\text{Rb}^{85}$  and  $\text{Rb}^{87}$ ), then the ratio of the species frequencies is the product of the magnetic moment ratio, the inertial mass ratio, and the gravitational mass ratio. The magnetic moment ratio can be precisely determined in an auxiliary resonance experiment as can the inertial mass ratio (*e.g.*, by measuring the corresponding ion cyclotron resonance frequency ratio, correcting for electron mass). Using field independent transitions, a high-precision Eötvös experiment results from this experiment sequence and a product of resonance frequency ratios. Performing the interferometer experiment at different altitudes then (in a fashion similar to the recent AFGL tower experiment) allows a measurement of the effects of a 5th force.

## REFERENCES

- Clauser, J. F. 1988, *Ultra-high Sensitivity Accelerometers and Gyroscopes Using Neutral Atom Matter-Wave Interferometry*, Proc. of the International Workshop on Matter Wave Interferometry in Light of Schrödinger's Wave Mechanics 14 to 16 September 1987, Technical Univ. of Vienna, and Atominstitut der österreichischen Universitäten (to appear in *Physica*)

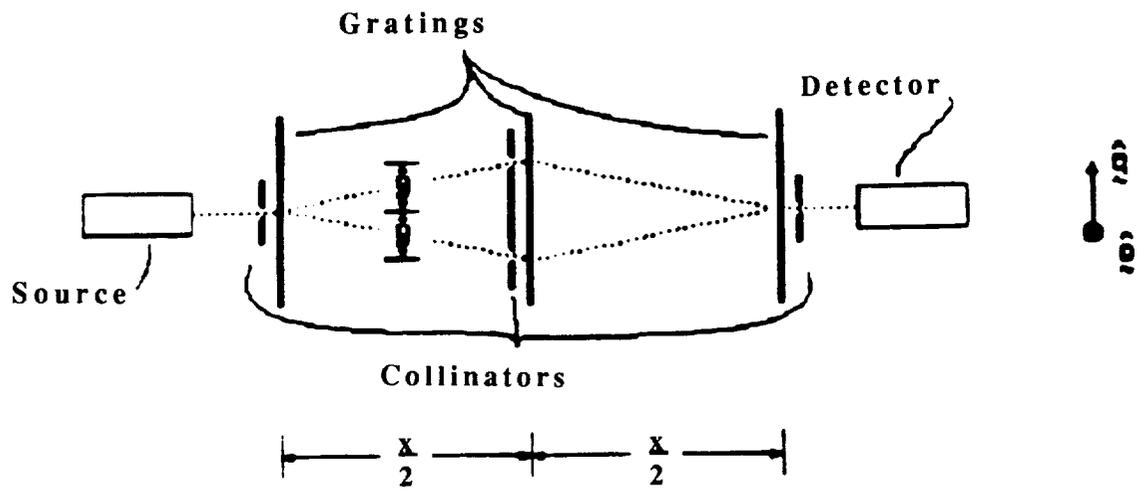


FIG. 1.— Separated Beam Interferometer

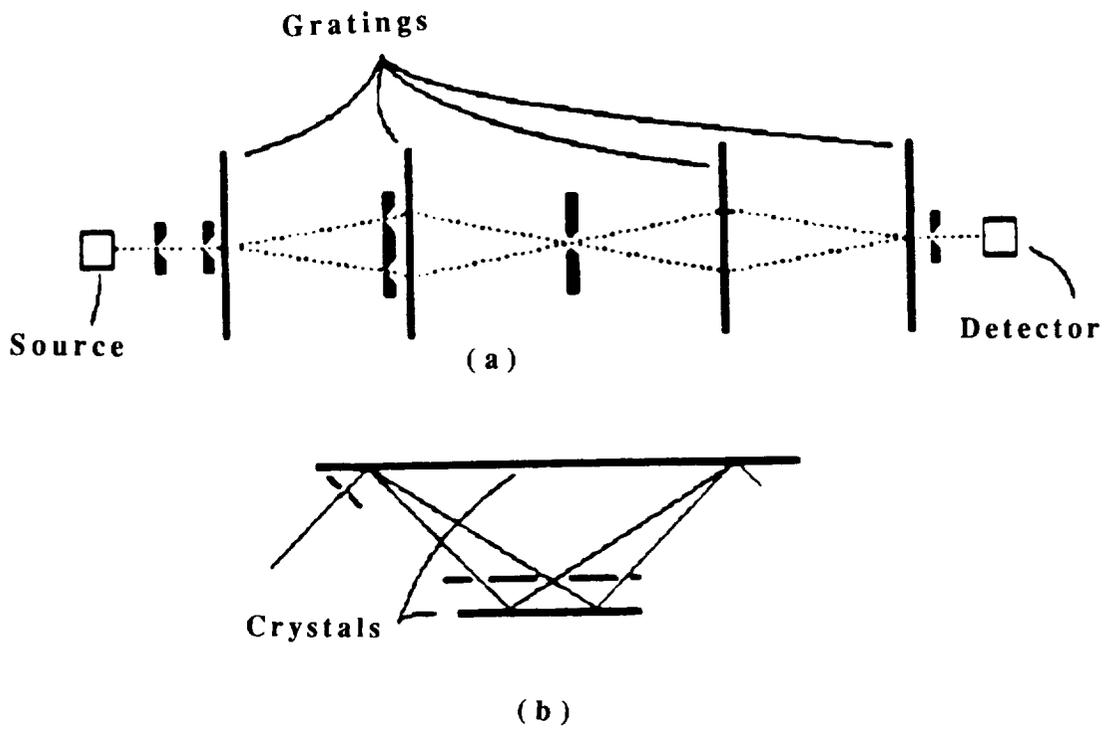


FIG. 2.—Gradiometer Configurations

## DISCUSSION

FAIRBANK: Won't Newtonian forces overwhelm the signals you are trying to measure? Indeed, the Stanford experiment requires a nearly perfectly spherical ball, negligibly diamagnetic, etc. Minute deviations will cause anomalous precessions.

CLAUSER: If the spacecraft rotates slowly about the star tracer axis, then a fixed bias (e.g. due to spacecraft mass asymmetries) will yield no signal synchronous with the rotation. If an atom with  $J=0$ ,  $I=0$  (e.g. an alkaline earth or noble gas) is used, there will be no magnetic influence on the atoms. For the configuration of Fig. 1, suppose the triangular areas of the input and output ends of the interferometer are imbalanced by a part in  $10^{10}$ , due to a grating spacing error of 1mm out of 100m. Then a fringe shift comparable to that expected for the Lense-Thirring precession will be produced by a gravitational gradient of about 0.3 E, far greater than that expected in orbit. Warping of the spacecraft axis by thermal gradients and/or magnetostriction may cause a shift; however these can be removed by the aforementioned stabilization using the *in-situ* electromagnetic fringe reference.

WEISS: Won't thermal fluctuations wipe out your signal when you extrapolate the sensitivity to systems of large dimension, especially for your proposed gravitational wave detector?

CLAUSER: The proof masses are the atoms themselves, which are at 100 mK. The conditions for coherence (seeing fringes) are readily satisfied.

WEISS: No, I am referring to thermal fluctuations of the spacecraft and/or interferometer elements.

CLAUSER: Lets design a simple spacecraft and consider its primary bending mode. Suppose the instrument is 100 m long and is made from a carbon-fiber truss frame with 5:1 aspect ratio. This material has a density of  $1.6 \text{ g cm}^{-3}$  and an elastic modulus of  $1.3 \times 10^6 \text{ dyne cm}^{-2}$ . A frame member cross section of  $1 \text{ cm}^2$ , yields an overall frame weight of 32 kg for two bars 100 m long. It will have a bending spring coefficient of  $x = 1.3 \text{ dyne per cm lateral end deflection}$ . Putting  $kT/2$  thermal energy at  $T=300\text{K}$  into this bending mode yields an end deflection of  $Dx_{\text{rms}} = 1.8 \times 10^{-3} \text{ m}$ , which is about the same as the grating spacing time fringe fraction (1 part in  $10^3$ ) used for most of the experiments discussed above. OK, so you integrate a little longer. The exception is the proposed gravitational wave detector, which has a grating spacing  $10^4$  smaller, while a fringe is split to a part in  $10^5$ . Thus, you are correct in fingering the gravitational wave detector as the most thermally sensitive. Its implementation thus requires a gain for the servo system that stabilizes the gratings relative to the electromagnetic fringe reference to be of order  $10^6$ . I agree that such engineering is not trivial, but I think it is doable, and with due respect to the other contributors, less demanding than many of the proposals discussed at this conference. I propose this as an easier method to detect long period gravitational waves, not an easy method!

SONNABEND: What about the  $W^2$  effects I mentioned in my talk on gradiometry. Won't these be important.

CLAUSER: I believe these effects represent centrifugal acceleration's lack of collinearity. In a precision experiment, of course, the effect must be considered (as it was in Ref. 1). The effect was neglected here for simplicity of presentation. Since  $W$  is small in all of the experiments discussed here,  $W^2$  effects will be correspondingly negligible.

SONNABEND: Your instrument does cancel out the  $w$  terms in your gradiometer, but not the  $w^2$  and  $w$  term. In this respect, your instrument is the same as everyone else's. It measures the intrinsic tensor.

CLAUSER: You're right.

