news and views

Dodging Heisenberg

from N. MacDonald

THE ultimate limit to the precision of physical measurements is set by quantum considerations. Any amplifier is noisy because of zero-point energy. All mechanical measurements, for example on the massive oscillators used in attempts to detect gravitational waves, are limited in precision in so far as they involve simultaneous measurement of position and momentum and so run up against the Heisenberg uncertainty principle

$$\Delta x \Delta p \gtrsim \tfrac{1}{2} \hbar$$

In a recent paper K. S. Thorne, R. W. P. Drever, C. M. Caves, M. Zimmermann and V. D. Sandberg (*Phys. Rev. Lett.* **40**, 667; 1978) propose a radical new approach to this limitation. One variant of this approach has simultaneously been advocated by a group in Moscow (Braginsky, Vorontsov & Halili *J.E. T.P. Lett.* March; 1978).

Both these groups are engaged in planning experiments for the detection of gravitational waves. Both the first generation of gravitational wave detectors, and those at present under construction, are very far from the quantum limit of precision, and also very far from the precision at present considered necessary if one is to be able to detect several gravitional wave pulses per year. The significance of the quantum limit in this context was first pointed out by Braginsky. The basic quantities needed to assess the precision of measurements on the oscillation of a bar of mass M, length L, are the duration T of the pulse one hopes to detect, and the fractional strain $\delta L/L$ caused by this pulse. T is thought to be of the order of 10^{-3} s, while pulses originating from supernovae out as far as the Virgo cluster of galaxies, and likely to arrive at the rate of three each year, are thought likely to yield $\delta L/L$ about 10^{-20} to 10^{-21}.

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Approximating the oscillating bar by a mass on a spring one is, in effect, measuring the extension L and the velocity $\delta L/T$. The uncertainty principle thus leads to an error Δ in the strain given by

$$\Delta^2 \gtrsim (\Delta L)^2 + (\tfrac{1}{2} \frac{\hbar}{\Delta L} \frac{T}{M})^2$$

which leads to the estimate

$$\Delta \gtrsim (\frac{\hbar T}{M})^{\frac{1}{2}}$$

For a mass of 10 kg this is about 10^{-19}, and it falls only as the inverse square root of the mass for more massive oscillators. So even if other sources of imprecision are removed from the planned third generation of detectors, so that detection of the faint pulses is in prospect, some way round this quantum limit must be found.

Braginsky proposed a few years ago to circumvent this difficulty by means of direct measurement of the energy of the oscillator, that is to say of the number of quanta (phonons) in the excitation of the bar. This approach encounters several difficulties. For example to count the number n of quanta without creating or destroying any quanta requires that the interaction Hamiltonian H, expressing the coupling of the oscillator and the detector, must commute with the number operator N, which means that H must involve the squares of the coordinate and momentum of the oscillator displacement. With such minute displacements this would be very hard to achieve.

The new proposal is compatible with linear coupling of the oscillator and the detector. In terms of the complex amplitude

$$X_1 + iX_2 = (X + iP/M)\, e^{i\omega t}$$

it is apparent that an alternative pair of conjugate variables to the usual X and P are X_1 and X_2. Any device requiring measurement of both X_1 and X_2 runs up against the uncertainty principle. However it was noted by Thorne that it is possible to get all the information needed about the passage of a gravitional wave pulse from measurements of X_1 alone.

Since the best way to bring out the physical implications of the uncertainty principle is by means of 'thought experiments', it may be helpful to think about the stroboscopic illumination of an ideal pendulum. Such a stroboscopic experiment is mentioned in the paper by Thorne *et al.*, and this aspect of the problem is discussed in more detail by Braginsky *et al.* The pendulum bob is illuminated by a flash of light and its instantaneous position x thus determined. But this precise measurement is paid for by delivery of an arbitrary recoil to the bob from the scattered photon. The bob acquires unknown momentum, and so the future position is, in general, unpredictable. However, if one illuminates only at intervals of half the period of the pendulum, one can predict that values $-x, x, -x, ..$ will be obtained. This amounts to measuring the eigenvalue of X_1 taking the time t of the first flash as one at which $\sin(\omega t) = 0$, so that $X_1 = \pm X$ at each instant at which the bob is illuminated, and the eigenvalue $x_1 = x$.

Continuous measurement of X_1 requires modulation of the output of position and momentum transducers by $\sin(\omega t)$ and $\cos(\omega t)$, without the intervention of any new source of noise. For example Thorne *et al.* discuss in some detail a torsion balance device for X_1 measurements for an electrical oscillator. There are severe difficulties in the way of a practical realisation of these measurements, but the principle of the new approach is applicable, not only for mechanical detectors of gravitational waves, but for detectors of any weak but classical disturbance. □

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