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OBSERVATION OF THE THERMAL FLUCTUATIONS OF A GRAVITATIONAL-WAVE DETECTOR*

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We report operation of apparatus to measure the Fourier transform of the Riemann curvature tensor at sensitivity limited by the thermal fluctuations. The gravitational interaction drives a mechanical system which in turn is coupled to the electromagnetic field. Strains as small as a few parts in 10^{16} are observable for a compressional mode of a large cylinder.

The normal modes of an elastic body having appropriate symmetry may be excited by the dynamical curvature tensor.[1] A detector of gravitational radiation[1] may consist of a carefully suspended mass with instrumentation to observe the amplitude of the normal modes. We report observation of the thermal fluctuations of a $1\frac{1}{2}$-ton aluminum cylinder of length ~150 cm and diameter ~61 cm in the vicinity of its lowest compressional mode near 1657 cps (see Fig 1).

At these frequencies the center of mass[1] of the detector on the earth's surface behaves almost as though it were in free fall.[1] A normal coordinate[1] system is appropriate with the pole at the center of mass of the detector. In these coordinates, with the axis of the cylinder in the X^1 direction, the detector output measures the Fourier transform of the component R_{1010} of the Riemann tensor.

The mean squared relative displacement of the cylinder end faces, $\langle X^2\rangle$, associated with the thermal fluctuations is given for each degree of freedom approximately by

$$\tfrac{1}{2}m\omega^2\langle X^2\rangle = \tfrac{1}{2}kT. \quad (1)$$

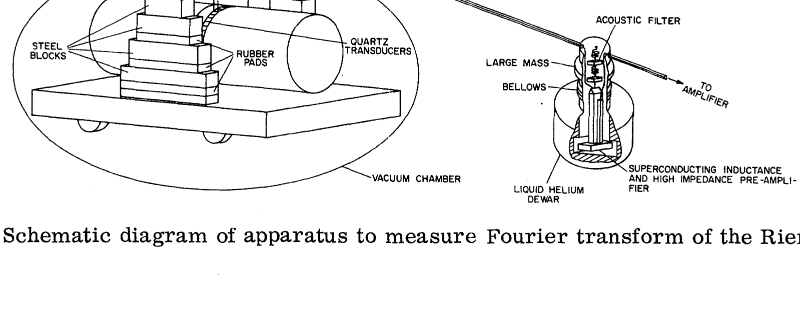

FIG. 1. Schematic diagram of apparatus to measure Fourier transform of the Riemann tensor.

Here m is the mass, ω is the angular frequency, k is Boltzmann's constant, and T is the absolute temperature. Observation of the thermal fluctuations implies detection of root-mean-square displacements $\sim 2\times 10^{-14}$ cm over a meter and a half or the remarkably small strains of a few parts in 10^{16}.

The detector is suspended in a vacuum chamber on acoustic filters. Quartz strain gauges convert the mechanical strains to voltages. To achieve optimum performance a high impedance must be employed in the output circuit. This is accomplished by resonance of the capacity of the quartz-strain gauges with an inductance. To achieve an impedance $>10^9\ \Omega$ and for noise reduction the inductance and preamplifier are maintained at liquid-helium temperatures. While the inductance is at 4°K, other parts of the system are at room temperature. Noise-generator measurements indicate that when the system is detuned, its noise temperature is in the vicinity of 50°K.

Since the detection is ultimately concerned with observation of the piezoelectrically induced electric field we may think of the gravitational interaction as producing photons which are detected.

Figure 2 is a tracing of a recorder record proportional to the noise power output. Shortly before the six-hour mark the preamplifier tuning was changed slightly to decouple it from the cylinder. The large change in noise represents primarily the effect of the thermal fluctuations of the cylinder. The residual noise after six hours represents the fluctuations in the resonant circuit and preamplifier. Thus strains of a few parts in 10^{16} are giving a readily observable effect.

It is currently believed that the collapse of a supernova core or a double neutron[2] star might result in emission of large amounts of gravitational radiation with increasing frequency as the collapse proceeds. Calculations indicate that the sensitivity reported here might under favorable conditions result in detection of such events within our galaxy.[3]

Sinsky[4,5] of this university has succeeded in generating a gravitational induction-field Riemann tensor by driving a small (20-cm diameter) aluminun cylinder acoustically in a vacuum chamber and detecting the gravitational signal with the instrument reported here. Thermal fluctuation sensitivity limits imply that a harmonic Riemann tensor (or one with amplitude over the apparatus bandwidth) exceeding 10^{-33} cm^{-2} can be detected and this is consistent with Sinsky's results which will be reported in a subsequent paper. For a useful comparison we note that the static curvature at the earth's surface is $\sim 10^{-26}$ cm^{-2}.

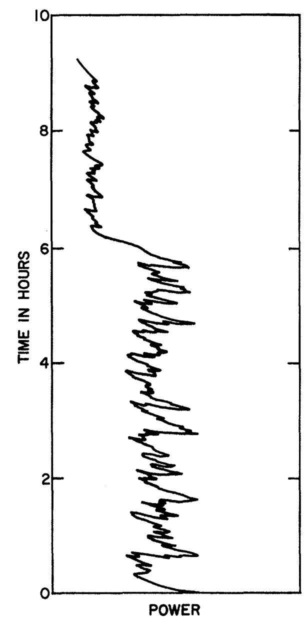

FIG. 2. Noise power output with cylinder tuned and detuned from preamplifier electronics.

We thank the U. S. Naval Ordnance Laboratory for assistance in development of the superconducting coils. We also acknowledge with thanks the valuable work of Dr. Robert L. Forward in mechanical design, Dr. David M. Zipoy in development of the suspension and computer program for noise calculations, and Mr. Richard Imlay in design of the acoustic filters.

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COSMIC-RAY ELECTRON LIFETIMES IN THE GALACTIC DISK AND HALO*

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Recent measurements of cosmic-ray electrons of energies 12 to 350 BeV[1,2] indicate that their differential energy spectrum can be fitted by a power law with spectral index of 2.1 ± 0.2. This index is the same as that found at energies of a few billion electron volts,[3,4] which seems to be in contradiction with the expected steepening of the spectrum because of synchrotron and inverse Compton losses. As a result of this discrepancy, Daniel and Stephens[2] concluded that either the 3°K black-body radiation does not exist or there is an additional high-energy electron source with spectral index 1.1.

We propose instead that the observed high-energy electron spectrum results from a cosmic-ray mean lifetime in the galactic disk that is shorter than the lifetime against radiation losses by these electrons, but long enough to establish a measurable equilibrium flux.

The calculations of Felten and Morrison[5] show that the intergalactic electron intensity required to produce the diffuse gamma-ray background flux by the inverse Compton mechanism is more than three orders of magnitude less and of a steeper spectral shape than the electrons observed at the earth. Thus, we shall assume that the sources of the electrons, whether of primary or secondary origin, are located in the galactic disk. The electrons produced in the sources spend a time τ_d in the disk, after which they leak out into the halo, where they spend a time $\tau \gg \tau_d$ before they leak into the intergalactic medium. Since τ is much larger than τ_d, the electrons in the halo are freely exchanged[6] between disk and halo. The equilibrium density in the halo, $\eta_h(E)$, satisfies

$$\frac{\eta_h(E)}{\tau} - \frac{\partial}{\partial E}\left[\frac{dE}{dt}\eta_h(E)\right] = \frac{\eta_s(E)}{\tau_d}\frac{V_d}{V_h}, \quad (1)$$

where $\eta_s(E)$ is defined by

$$\frac{\eta_s(E)}{\tau_d} - \frac{\partial}{\partial E}\left[\frac{dE}{dt}\eta_s(E)\right] = q(E), \quad (2)$$

and where $q(E)$ is the number of electrons produced per unit volume per second in the disk, V_d and V_h are the disk and halo volumes, respectively, and dE/dt is the energy-loss rate resulting from synchrotron and inverse Compton losses. For a mean magnetic field of 3×10^{-6} G and a black-body photon density of 0.4 eV/cm^3, we obtain $dE/dt = 6 \times 10^{-17} E^2$ (BeV/sec). The equilibrium density which should be measured in the disk is

$$\eta_d(E) = \eta_s(E) + \eta_h(E).$$

Assuming that $q(E) = q_0 E^{-\Gamma}$, Eq. (2) can be solved analytically, and for $E \ll E_1 = 1.6 \times 10^{16}/\tau_d$ BeV its solution is

$$\eta_s(E) = q_0 E^{-\Gamma}\tau_d,$$

whereas for $E \gg E_1$, η_s varies as $E^{-\Gamma-1}$. Using this functional form for η_s, we can solve Eq. (1) for η_h in a similar fashion, where now the break in the spectrum comes at $E_2 = 1.6 \times 10^{16}/\tau$ BeV. Then for $E < E_2$, the disk density is

$$\eta_d(E) = q_0 E^{-\Gamma}\tau_d\left[1 + \frac{V_d}{V_h}\frac{\tau}{\tau_d}\right]. \quad (3)$$

The factor $V_d\tau/V_h\tau_d$ is the ratio of the time a halo electron spends in the disk to the disk lifetime τ_d. At energies less than E_2 where the halo leakage life is shorter than the lifetime against energy losses in the halo, this ratio is a measure of the re-entrant halo electrons in the disk. For $E_2 < E < E_1$, the energy-loss lifetime in the halo is shorter than τ but longer than τ_d; thus re-entrant electrons from