ods are manifold. We plan to apply it to a sys-
tematic survey of pseudo magnetic moments of
stable nuclei.

[1]A. Abragam, G. L. Bacchella, H. Glättli, P. Meriel,
J. Piesvaux, and M. Pinot, C. R. Acad. Sci., Ser B 274,
423 (1972).
[2]A. Abragam, G. L. Bacchella, H. Glättli, P. Meriel,
J. Piesvaux, M. Pinot, and P. Roubeau, in Proceedings
of the Seventeenth Congress Ampère, Turku, Finland,
21−26 August, 1972 (North-Holland, Amsterdam, to be
published).
[3]A. Abragam, in Trends in Physics (European Physi-
cal Society, Geneva, Switzerland, 1973), p. 177.
[4]E. Fermi, Ric. Sci. 7, 13 (1936).
[5]V. Barytchevski and M. Podgoretzki, Zh. Eksp. Teor.
Fiz. 47, 1050 (1964) [Sov. Phys. JETP 20, 704 (1965)].
[6]L. Koester and W. Nistler, Phys. Rev. Lett. 27, 956
(1971).
[7]C. G. Shull and R. P. Ferrier, Phys. Rev. Lett. 10,
295 (1963).
[8]N. Ramsey, Molecular Beams (Oxford Univ. Press,
Oxford, England, 1956).
[9]See, for instance, A. Abragam, Principles of Nucle-
ar Magnetism (Clarendon, Oxford, England, 1961).

New Gravitational Radiation Experiments*

J. Weber, M. Lee, D. J. Gretz, and G. Rydbeck
University of Maryland, College Park, Maryland 20742

and

V. L. Trimble†
University of California, Irvine, California 92664, and University of Maryland, College Park, Maryland 20742

and

S. Steppel
*Stanford Linear Accelerator Center, Stanford, California 94305, and
University of Maryland, College Park, Maryland 20742*
(Received 18 June 1973)

Squared time derivatives of output powers of the Argonne and Maryland gravitational
radiation detectors are written on magnetic tapes at Argonne and Maryland every 0.1 sec.
A computer files the threshold crossing times. A coincidence is a pair of identical cross-
ing times of both tapes. The accidentals rate is measured by repeating the procedure for
a sequence of time delays in either channel. A significant excess of coincidences is found
at zero delay.

Experiments.—Interaction of something with
the antenna[1-3] will increase or decrease the en-
ergy depending on phase relations between the
Brownian motion and the increase of velocity.
To observe such changes, the derivative of the
power is taken by an analog device, squared and
written on magnetic tape every 0.1 sec with 6-bit
accuracy (64 intervals). Without further filtering,
the magnetic tape from recorders at both sites is
read by the Univac 1108 computer. The computer
lists the times each channel crosses a threshold
which is chosen to give about 4000 crossings per
day. The computer looks for identical crossing
times, and prepares a list of coincidences. Then,
one file is delayed by 0.1 sec and a new list of
coincidences prepared, and so forth for other
amounts of delay. All operations are performed
by the computer. The number of coincidences is
shown as a function of delay by the histogram of
Fig. 1(a). The true coincidence rate is the num-
ber of coincidences found when no delay has been
introduced minus the average value with various
delays. For 21 days we observe an excess of 139
coincidences representing more than 5 standard
deviations from the mean.

For most of the time of these experiments the
telephone line was in use, and both Argonne and
Maryland outputs were written on one tape at
Maryland, while the Argonne output alone was
written on tape at a second recorder at the Ar-
gonne National Laboratory. The histogram of
Fig. 1(b) shows the number of coincidences re-
corded by the computer from a study of the single
Maryland tape. The somewhat smaller number
of coincidences at zero delay associated with
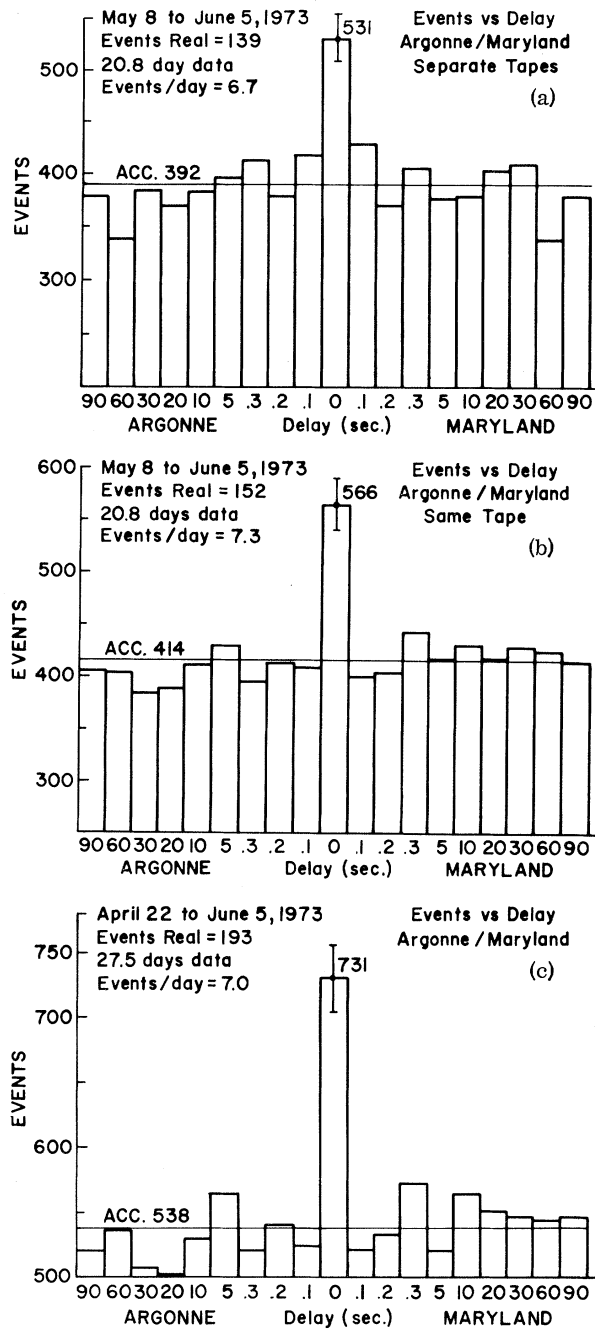Fig. 1(a) is due to irregularities in the two-tape

FIG. 1. Coincident events versus time delay; real events are zero-delay value minus accidentals. (a) Separate recorders; (b) all data recorded at Maryland using telephone line data link; (c) extended period, using telephone data link.

synchronization which introduce one-quantization-interval glitches (±0.1 sec) in one tape relative to the other. These irregularities are not present when all data are written on one tape.

Thus most of the missing zero-delay coincidences in 1(a) are found in the ±0.1-sec bins. The telephone transmission of data and analog-digital-analog conversion do not produce extra coincidences. The digital telephone equipment transmits only from Argonne to Maryland and saturates at 5 V; there is, therefore, no possibility of strong-field propagation down the chain of terminals and microwave relay links from Argonne to Maryland.

Figure 1(c) gives results for the extended period 22 April–5 June 1973, making use of the telephone line throughout. The zero-delay excess is 7 standard deviations.

Figure 1 includes all data for the periods listed which could be read by the computer. The excess of coincidences at zero delay varied between 12 and 40 per 4-day tape.

After these experiments were completed the telephone line was disconnected altogether and the zero-delay excess of coincidences remained. The use of isolated recorders with no telephone connection does not guarantee the validity of these results. We can imagine defective recorders which write spurious signals on tape at certain times, for example, at the beginning or end of a data block. Since these operations are controlled by synchronized clocks additional coincidences could be generated. For the experiments reported here the data were carefully searched for such effects. None were found. Furthermore, the telephone line enabled us to carry out a parallel experiment utilizing an on-line computer to record coincidences with and without a 4-sec delay. Results were consistent with Fig. 1.

Effect of thresholds on coincidence rates.—A 4-day tape with data giving a zero-delay coincidence excess of 40 was processed with a series of threshold crossing rates varying from one per minute to 11 per minute. At 2 crossings per minute the zero-delay excess is 30 and approximately equal to the accidentals. The zero-delay excess increases linearly to about 120 at 7 crossings per minute. The accidentals rate increases quadratically to about 480 at 7 crossings per minute. Beyond 8 crossings per minute the zero-delay excess decreases. The ratio of zero-delay excess to the accidentals can be increased if pulse heights are measured and a classification scheme for the coincidences employed following earlier work.[3]

Detectors and their sensitivity.—The gravitational radiation detectors are the same aluminum cylinders described in earlier experiments.
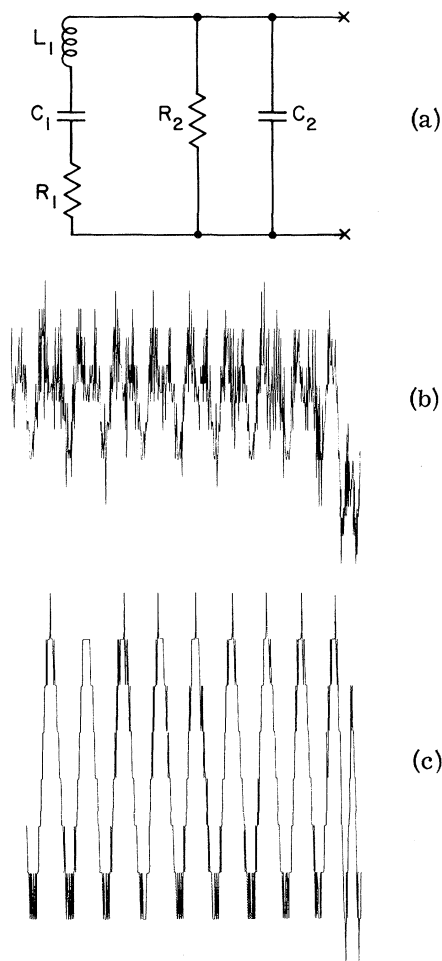
FIG. 2. Sources of noise. (a) Equivalent circuit near lowest frequency longitudinal mode. $L_1 = 750$ H, $C_1 = 1.22 \times 10^{-11}$ F, $R_1 = 40$ Ω, $C_2 = 7 \times 10^{-8}$ F, $R_2 = 400\,000$ Ω. (b) Plot of digitized two channel voltages squared and summed by the computer versus time as abscissa. (c) Plot of analog sum of squares of two channel voltages versus time as abscissa.

Lead zirconate titanate transducers[2] are bonded to the cylinders and their output voltage is amplified by a low-noise field-effect transistor followed by other amplifiers.

The approximately square-law devices employed are those of earlier experiments. A 1.6-Hz bandwidth is obtained by a two-stage Butterworth filter on the phase-sensitive detector. It has 12-dB rolloff per octave (0.8 Hz). The amplifier has a bandwidth of 12 Hz, centered at the cylinder mode frequency 1661 Hz. The differentiator is a resistance-capacitance filter.

The noise performance and sensitivity are determined in the following way. Direct measurements and theory show that, in the vicinity

of the instrumented cylinder mode frequency, the impedance seen at the transducer terminals corresponds to that of the circuit shown in Fig. 2(a). L_1 is the inductance equivalent of the mass. The equipartition theorem predicts that the Brownian motion of the cylinder will give a noise current with mean squared value

$$\langle I_B{}^2 \rangle = kT/L_1. \tag{1}$$

The output power P will consist of three parts: (a) amplifier internal noise, (b) amplified noise associated with the transducer losses, and (c) amplified noise due to the current given by (1).

(c) covers only the very narrow band of the cylinder mode while (a) and (b) extend over the demodulator bandwidth $\Delta\nu$ centered about the mode frequency ν_0. Let A be the power gain and let $AN(\nu)\Delta\nu$ be the output power due to (a) and (b). Hence the total output power is

$$P = AN(\nu)\Delta\nu + AkT/4\pi^2\nu_0{}^2 L_1 C_2{}^2. \tag{2}$$

We may measure $N(\nu)$ in the following way. A calibrated noise generator is arranged to be a current source with power spectral density $i_n{}^2(\nu)$. Extreme care is required to insure that connecting the noise generator does not degrade the noise performace. Let $Z(\nu)$ be the impedance at terminals XX of Fig. 2(a). With noise generator turned on we observe increased power P' with

$$P' = P + \int_{\nu_0 - \Delta\nu/2}^{\nu_0 + \Delta\nu/2} A i_n{}^2(\nu) |Z(\nu)|^2 d\nu. \tag{3}$$

Everything is known in (2) and (3) except $N(\nu)$ which is, therefore, determined by observation of P and P' and a knowledge of $Z^2(\nu)$ and $i_n{}^2(\nu)$.

We observed that for bandwidth $\Delta\nu = 1.6$ Hz, the ratio

$$\frac{kT/4\pi^2\nu_0{}^2 L_1 C_2{}^2}{N(\nu)\Delta\nu} = 18. \tag{4}$$

Equation (4) determines the sensitivity.[2,4] This value was confirmed by a detailed study of the power spectrum making use of a very narrow band tunable filter, and by autocorrelation analysis of tape recordings of the output of a linear demodulator.

We can also calibrate by applying an electrostatic force to a plate close to one end of the cylinder. Pulses are applied at 830 Hz, since the force varies as the square of the field. We know that the driving oscillator and associated circuits do not generate significant Fourier components within the amplifier pass band, since we observed no response from a 1.6-Hz band filter

detuned from the cylinder mode frequency. If the initial velocity is zero, the energy U gained by the cylinder after time t is

$$U = \epsilon_0^2 E^4 S^2 t^2 / 64M, \qquad (5)$$

where ϵ_0 is the permittivity of free space, E is the peak value of the electric field, M is the cylinder mass, and S is the area of the plate. All calibration pulses referred to in the following discussion are the zero initial velocity values de-

fined by (5).

The squared derivative of the power will vary over a wide range for calibration pulses of a given magnitude depending on phase relations between the added velocity and initial velocity associated with the Brownian motion. Thus a very small calibration pulse $kT/60$ may be seen as in Fig. 3 to appear in the output as a large squared derivative of power signal.

The following table summarizes our observations:

Pulse energy	Number of pulses	Number observed in squared derivative of power to exceed twice the mean	Estimate of coincidence detection efficiency
kT	60	48	0.20
$kT/10$	50	26	0.05
$kT/60$	60	15	0.01

Disappearance of coincidences.—We have not observed coincidences on all data tapes, or for all apparently reasonable computer programs. In all cases the disappearance of coincidences was found to be a consequence of deterioration
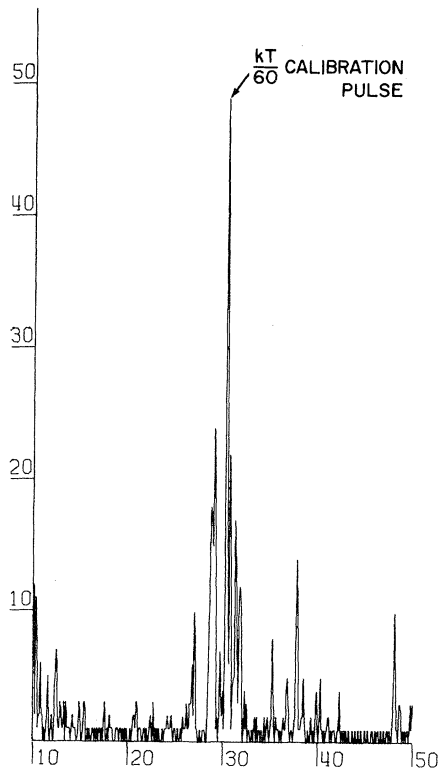

FIG. 3. Calcomp plot of 40-sec block of magnetic tape showing $kT/60$ calibration pulse. The abscissa is in seconds. The ordinate is the square of the derivative of the power.

of the noise performance of one of the gravitational radiation detectors, or additional noise introduced as a result of changes in computer program. These will increase the accidentals rate and leave such a small excess at zero delay that it vanishes in the fluctuations. For a period of about a month additional noise was inadvertently introduced in the following way.

A demodulator is employed to obtain the envelope of the amplified cylinder oscillations. There are two channels needed in consequence of the fact that the phase of the cylinder oscillations is a random variable. One channel is synchronously switched by a quartz oscillator tuned to the detector cylinder frequency. A second channel is switched by the same quartz oscillator with a phase shift of $\frac{1}{2}\pi$. To obtain the total power the two channel outputs are squared and summed.

It is desirable to record both channels separately on magnetic tape and prepare a computer program to search for changes in both amplitude and phase of the detector output. Study showed that the use of 64 quantization intervals for each channel introduced a large quantization error because one channel or the other frequently had small values of voltage, resulting in a large percentage error. Use of the computer to square and sum to give the power produced an unacceptable amount of noise, which was absent when the power was obtained by squaring and summing in an analog device without quantization.

Figure 2(c) shows the power output of the analog device and Fig. 2(b) shows the additional

noise obtained by squaring and summing the 64 interval quantized components of a test signal, with a computer.

The new experiment now is yielding about seven coincidences per day, corresponding to increases in energy exceeding $kT/100$. We are pleased to acknowledge valuable discussions with G. R. Ringo, R. Muller, N. S. Wall, H. Brandt, and D. H. Douglass.

[1]J. Weber, Phys. Rev. 117, 306 (1960), and General Relativity and Gravitational Waves (Interscience, New York, 1961), Chap. 8, and Relativity, Groups, and Topology (Gordon and Breach, New York, 1964), p. 875.

[2]J. Weber, in "Gravitational Radiation Experiments and Instrumentation, Proceedings of the International School of Physics 'Enrico Fermi,' Course 55," 1972 (Academic, New York, to be published).

[3]J. Weber, Phys. Rev. Lett. 24, 276 (1970).

[4]G. Gibbons and S. Hawking, Phys. Rev. D 4, 2191 (1971).

Measurement of σ_{tot} in Proton-Proton Scattering in Pure Spin States*†

E. F. Parker and L. G. Ratner
Accelerator Division, Argonne National Laboratory, Argonne, Illinois 60439

and

B. C. Brown, S. W. Gray, A. D. Krisch, H. E. Miettinen, and J. B. Roberts
Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan 48104

and

J. R. O'Fallon
Department of Physics, St. Louis University, St. Louis, Missouri 63103
(Received 14 August 1973)

An experiment was done using the new accelerated polarized proton beam at the Argonne National Laboratory zero-gradient synchrotron and a polarized proton target. The total cross section for proton-proton scattering at 3.5 GeV/c was measured in the spin states ↑↑ and ↑↓ perpendicular to the beam direction. The two cross sections were found to be equal within the experimental error of ±5%.

During recent years there has been an increasing interest in the importance of spin in high-energy strong interactions. This has come from the very successful experiments using polarized proton targets at Lawrence Berkeley Laboratory,[1] CERN,[2] and Argonne National Laboratory[3] (ANL). For the past few years our group has worked together with the accelerator division at ANL on a project to accelerate polarized protons at the zero-gradient synchrotron (ZGS). A beam of 3×10^8 polarized protons has now been accelerated up to 6 GeV/c, with a polarization of $(62 \pm 15)\%$.

The polarized protons originate in a polarized ion source[4] which gives 8 μA of 20-keV protons with a polarization of $(75 \pm 7)\%$. This source was placed in the new preaccelerator constructed by the ZGS staff[5] which accelerates the protons to 750 keV in a Cockcroft-Walton accelerating column. The protons are then fed into the main LINAC line by a switching magnet and then accelerated to 50 MeV by the LINAC. The polarization at 50 MeV is measured using a "polarimeter" which continuously measures the left-right asymmetry in proton-carbon elastic scattering at 60°, where the measured asymmetry parameter is $(85 \pm 7)\%$.[6] We found the 50-MeV beam polarization to be $(65 \pm 5)\%$. The polarized protons are then injected into the ZGS, accelerated, and then extracted and sent to the high-energy polarimeter, described below, where the polarization is measured.

The main problem in accelerating polarized protons in a synchrotron is "depolarizing resonances."[7,8] These occur when the Larmor precessional frequency becomes equal to an integer multiple of the betatron oscillation frequency, so that the proton gets a similar perturbation each time it passes through a fringe field or imperfection with a horizontal component. These perturbations then add coherently and can rapidly de-