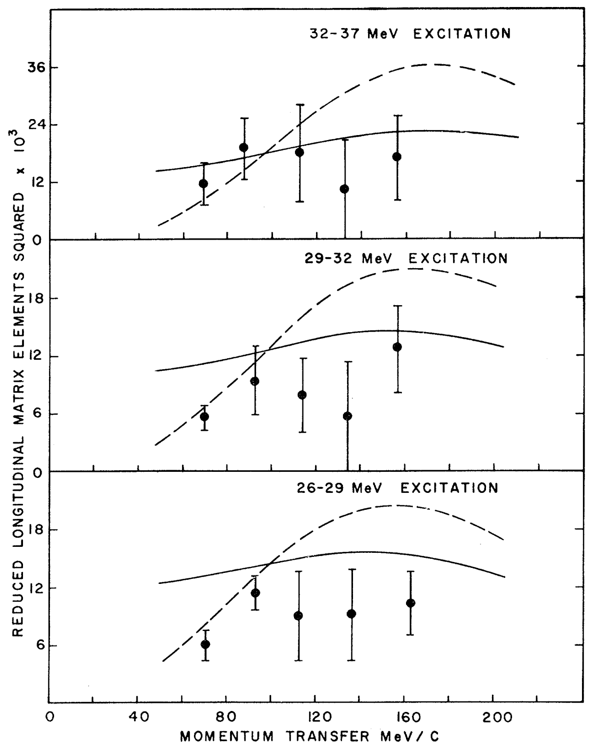

FIG. 3. Same as Fig. 2 except for longitudinal reduced matrix elements squared [oscillator-model (dashed line) and plane-wave (solid line) final-state nucleon wave functions].

very good for low excitation energies. The agreement with experiment in the giant-resonance region being better than the specific giant-resonance calculations is thus somewhat surprising. One would also expect that oscillator wave functions for the final-state nucleons would be better for low momentum transfer, and plane waves more realistic for higher momentum transfer. There is some evidence for this behavior in the longitudinal matrix elements shown in Fig. 3.

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GRAVITATIONAL RADIATION EXPERIMENTS*

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A summary is given of the statistics and coincidences of the Argonne-Maryland gravitational-radiation–detector array. New experiments have been carried out. These include a parallel coincidence experiment in which one coincidence detector had a time delay in one channel and a second coincidence detector operated with no time delays. Other experiments involve observations to rule out the possibility that the detectors are being excited electromagnetically. These results are evidence supporting an earlier claim that gravitational radiation is being observed.

An earlier Letter[1] described an experiment involving coincidences of gravitational radiation detectors at Argonne National Laboratory and the University of Maryland. This is the first experiment which tests directly the dynamics of gravitational fields. The results may have significance for physics, astronomy, and cosmology. Further experiments were therefore carried out to verify claims that the coincidences were not all accidental and that neither seismic nor electromagnetic effects were causing them.

Statistics.—Each gravitational-radiation–detector voltage output consists primarily of the thermal fluctuations of the suspended cylinder's lowest frequency compressional mode. A coincidence is recorded if the output voltages of two detectors cross some arbitrarily set threshold in the positive direction within some small time interval Δt. A classification scheme is set up for the coincidences. For each class the number of observed coincidences is compared with the expected number of accidental ones. A significant excess of observed over expected accidental coincidences establishes that the detectors are being excited by a common external source.

Gravitational-radiation–detector output noise pulses are characterized by the number of times each pulse amplitude is equalled or exceeded, on the average, per unit time. For one detector, this average recurrence frequency is denoted by N_A, and for the other detector by N_B. Large pulses have small values of N_A and N_B since they rarely occur. Two pulses are considered coincident if their leading edges occur within a certain resolving time Δt. For convenience let us choose the day as the unit of time for all quantities. The probability that by accident alone an arbitrarily selected time interval Δt will be found to contain the leading edges of two pulses characterized by N_A, N_B is P_{AB} with

$$P_{AB} = 2N_A N_B (\Delta t)^2. \qquad (1)$$

The expected number of accidental coincidences with amplitudes exceeding those observed for an experiment with effective duration M days is η_{AB} with

$$\eta_{AB} = 2N_A N_B \Delta t M. \qquad (2)$$

A two-dimensional space may be employed with N_A and N_B as coordinates. Each coincidence is represented by a point in this space. The number of accidental coincidences for a certain range of N_A and N_B is proportional to the area associated with the given range. It is useful for some purposes to consider the number of accidental coincidences $\tilde{\eta}_{AB}$ for which the product $N_A N_B$ is equal to or smaller than some constant and neither N_A nor N_B exceeds some maximum value N_S. The integral under the hyperbola $N_A N_B$ = const then gives the result for $\tilde{\eta}_{AB}$ as

$$\tilde{\eta}_{AB} = 2N_A N_B \Delta t M[1 + \ln(N_S^2/N_A N_B)]. \qquad (3)$$

Expression (2) is employed to calculate expected accidental coincidences throughout this Letter except for the last entry in the table relating to the time-delay experiment, in which case expression (3) was employed.

The numbers N_A and N_B are more convenient to measure than other quantities which might be used, such as the ratio of pulse amplitude to mean value. The coincident pulse is included in the count for determination of N_A and N_B. If there is a discontinuity in slope of the leading edge of a coincident pulse, the height is measured to the point of discontinuity.

Thresholds for these experiments were set low, corresponding to between 1000 and 2000 crossings per day in each channel. This guaranteed that about one accidental coincidence per hour would be observed, as a check on the operations of both gravitational radiation detectors and the coincidence circuits. Each gravitational radiation detector has a relaxation time somewhat less than 20 sec, and after it crosses threshold its square-law detector output cannot cross again for about 10 sec. Let α be the number of crossings per day and let t_r be half the detector relaxation time. The effective number of days M is related to the number of days μ of experiment observation time by

$$M = \mu(1 - 2\alpha t_r) \qquad (4)$$

The coincidence detector is an on-line computer which operates in the following way. There are two channels. When one channel voltage exceeds threshold a pulse of duration δ is generated. If the second-channel voltage crosses threshold within a time shorter than δ, its emitted pulse will overlap the first channel pulse and this overlap generates a coincidence-marker pulse. This overlap must be a significant fraction of δ to generate the marker pulse. δ was measured by use of an oscilloscope. For each value of δ, the resolving time Δt was measured by doing counting experiments at low thresholds, employing (2) and (4). $\Delta t \approx \delta/2$.

For the experiments covering the period 1 January-30 November 1969 the apparatus was operational for about 300 days. From (4), with $\langle\alpha\rangle = 1200$ and $t_r = 1.2 \times 10^{-4}$ days, M is calculated as 214 days. The measured mean value for $\Delta t = 4.1 \times 10^{-6}$ days = 0.35 sec. A few arbitrary thresholds are chosen for N_A and N_B and the number of chance coincidences is compared with the number observed as follows:

Class	η_{AB} (Expected number of accidentals)	Coincidences observed
$N_A \leq 10$, $N_B \leq 10$	0.18	7
$N_A \leq 40$, $N_B \leq 40$	2.8	24
$N_A \leq 80$, $N_B \leq 80$	11	90
$N_A \leq 100$, $N_B \leq 100$	18	115

A considerable excess of coincidences over the expected number of accidental ones is observed and ascribed to gravitational waves. The significant coincidence rate is about one every two days.

The values N_A and N_B are obtained by visual inspection involving a period of time of the order of hours. Observed values are not true long-term averages and contain a statistical error, especially large for small values of N_A and N_B. In the space of N_A and N_B, each coincidence becomes a rectangle, with areas of rectangles increasing towards the origin. Therefore, too much significance should not be attached to small numbers of coincidences with small values of N_A and N_B.

A different analysis was employed in the earlier Letter.[1] The mean number of days n expected for each coincidence to occur accidently with amplitudes equal to or greater than those observed is obtained by setting $M=1$ in (2) and taking the reciprocal,

$$n=(2N_AN_B\Delta t)^{-1}. \tag{5}$$

Coincidences were considered accidental if (5) was comparable with or smaller than the duration of the experiment. The time-delay experiment to be described later verifies that (5) does describe the accidental coincidences reasonably well. Nonetheless, I agree with respected colleagues that earlier conclusions should have been based on the kind of tables given here employing either (2) or (3). Such a table for the first 81 days of 1969 has been presented.[2]

Resolution time and coincidence rate.—During the period 15 March through 15 April the resolving time Δt was 0.30 sec $=3.5\times10^{-6}$ days and from 16 April through 16 May Δt was cut to 0.15 sec $=1.7\times10^{-6}$ days. This produced no significant change in coincidence rate for those coincidences characterized by $N_A \leq 120$, $N_B \leq 120$. Results are as follows:

Class	Coincidences observed Resolving time 0.30 sec	 Resolving time 0.15 sec
$N_A \leq 40$, $N_B \leq 40$	1	2
$N_A \leq 120$, $N_B \leq 120$	9	9

These data are consistent with the idea that most of the coincidences classified by the above values of N_A and N_B are not accidental.

Time delay experiment.—It is more convincing if statistical arguments can be supported by some experimental procedure to measure the rate of accidental coincidences. The following experiment was carried out as indicated in Fig. 1. A second coincidence detector was set up with time delay of two seconds in one circuit channel, in a manner which did not alter the concurrent experiment with no time delays. The results for an observation period of twenty days are as follows:

Class		Expected number of accidental coincidences	Coincidences observed Delay channels	 Instantaneous channels
$N_A \leq 100$,	$N_B \leq 100$	1.2	0	11
$N_A \leq 120$,	$N_B \leq 120$	1.7	3	15
$N_AN_B \leq 6000$,	$N_S^2/N_AN_B < 30$	3.2	3	18

The marked reduction in coincidence rate for the coincidences in the delay channels is evidence that the gravitational-radiation detectors are being excited by a common source with propagation time between detectors substantially less than 2 sec. It is also evidence that the expected accidental coincidences are understood.

Electromagnetic and seismic effects.—Records of a seismic array which records surface displacements along three axes at bands within the range 0-1680 Hz were again examined for evidence of correlation with the coincidences. No significant correlations were observed.

Electromagnetic excitation is the most likely spurious effect, and considerable investigation has gone into the verification that this does not cause most of the coincidences. A procedure involving a third gravitational-radiation detector with cryogenically cooled long-relaxation-time electronics was employed for the earlier work.[1] A different method is now employed. A radio receiver with bandwidth

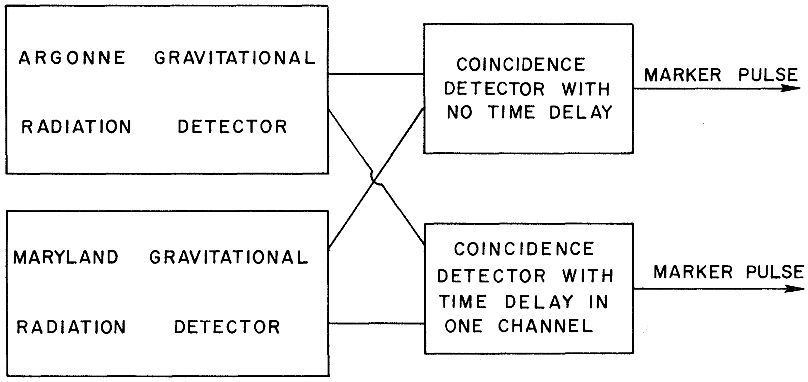

FIG. 1. Time-delay and instantaneous-channel coincidence experiment.

3 Hz centered at 1662 Hz is in use, with magnetic loop antenna. The cross section of this antenna is more than six orders greater than the measured electromagnetic-response cross section of the gravitational-radiation detectors. No significant correlations of local electromagnetic-field response with that of the gravitational-radiation–detector coincidences have been observed.

Cosmic rays. — There is no presently known aspect of the cosmic radiation which could account for the observed coincidence rate. Cosmic rays could account for some of the background at each site.[3] Some discussion of the theory of the response of the gravitational-radiation detector to cosmic radiation has been given.[2] Professor Wall, Professor Yodh, and Mr. Ezrow are carrying out experiments to study the cosmic-ray effects at the Maryland site.

Conclusion. — The time-delay and radio-receiver experiments support the earlier claim that gravitational radiation is being observed.

I have enjoyed stimulating discussions with L. Alvarez, F. Crawford, and T. Tyson.

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COMMENTS ON "EVIDENCE OF QUARKS IN AIR-SHOWER CORES"*

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McCusker and Cairns have published data on cloud-chamber tracks which they claim to be less ionizing than would be possible for singly charged particles, thus giving positive evidence for the existence of quarks of charge $\frac{2}{3}$. They neglected the effects of the relativistic rise of ionization in the gas of their cloud chamber and we believe they underestimated the errors of their drop count. Considering the fluxes of known particles in the cosmic rays it is concluded that their results can be explained as due to statistical fluctuations.

McCusker and Cairns[1] have recently published an event about which they say, "In a study of air-shower cores using a delayed expansion cloud chamber, we have observed a track for which the only explanation we can see is that it is produced by a fractionally charged particle." In that paper and in another by Cairns, McCusker, Peak, and Wolcott,[2] the Sydney group has reported a cloud-chamber study in which they have a total of 5 events with counts/cm along the track about one half that due to the majority of the particles traversing the chamber. They initially did not, however, consider the effects of the relativistic rise of ionization, and we believe they underestimated the experimental errors. Consideration of the distribution of ionization expected due to