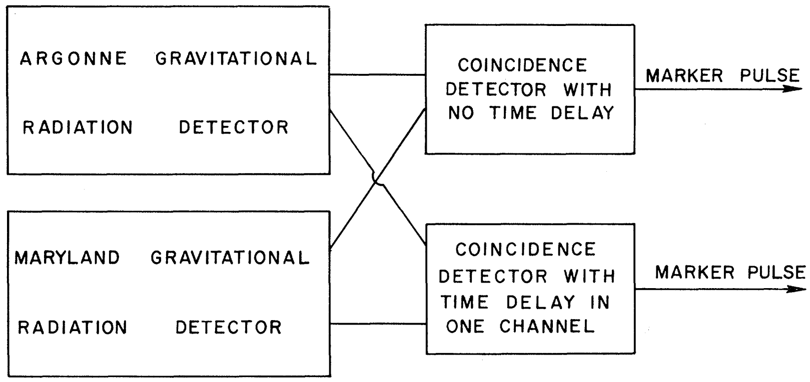

FIG. 1. Time-delay and instantaneous-channel coincidence experiment.

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 known particles convinces us that their results can be explained without requiring fractionally charged particles.

Relativistic Rise of Ionization. – The restricted energy loss for argon at 1.4 atm and 20°C has been calculated by Sternheimer.[3] The maximum energy transfer was taken as 500 eV (corresponding to a cluster of about 30 drops in a cloud chamber). The result is shown as the solid curve in Fig. 1. For the general method see Refs. 4-6. Inclusion of the appropriate amounts of water and alcohol vapor (for the conditions of the Sydney group) changes the ratio of I at minimum to I at plateau from 1.71 to 1.69. We note that for $\gamma(=E/m_0c^2)$ between 2 and 10, $I/I_{\min}$ is less than 1.1.

The experiments on the relativistic rise for noble gases show good agreement with the theory for helium[7] and xenon,[8] but a smaller rise than the theory predicts for argon.[7] Kepler et al.,[7] using an argon cloud chamber, found a relativistic rise about $\frac{3}{4}$ that predicted by theory. It thus appears that the best verified value to use for the experiment of McCusker et al.[1,2] is a ratio of minimum to plateau ionization of $1/1.51 = 0.66$. In Fig. 1, we have correspondingly shown an estimated curve (dashed curve) for the behavior of $I/I_{\min}$, based on Sternheimer's calculations, modified according to the data of Ref. 7. It should be noted that there is no single value for the relativistic rise in a particular gas. The appropriate value for this quantity depends on the pressure[4,5] and the method of detection.

Louttit[9] measured the relationship between ionization and drop count in a cloud chamber and found that for his case (50% Ar + 50% He at 67 cm Hg) when ionization increased from minimum to 1.6 times minimum, the drop count increased by a factor of 1.4, and for 2 times minimum the drop count ratio was 1.6. His drop count at minimum was about twice that of Kepler et al.[7]; so the results cannot be applied directly, but are indicative of the problem of saturation.

In order to determine the effects of possible saturation, experiments using ionization detectors should be calibrated with low-velocity particles of known ionization. It is possible that the discrepency between theory and experiment on the relativistic rise would be reduced if such a procedure were followed since most of the experiments assumed a strict proportionality between ionization and drop count.

Determination of Errors of Ionization. – Cairns et al.[2] measured the ionization by counting the number of drops in $\frac{1}{2}$-cm intervals on half-life-size enlargements, where intervals containing a δ ray were excluded. In this experiment the ionization is used as a tool to determine characteristics of the incoming particle, and not to measure the energy loss itself. The primary statistic is the number of ionizing collisions per centimeter the incoming particle makes in passing through the gas. The subsequent ionizations of the ejected electrons do not give information about the charge of the particle, except in the case of the infrequent very high-energy knock-on electron. The number of primary ionizing collisions is proportional to the total number of ions, but the statistical fluctuations are determined by the smaller number of primary ionizing collisions. This was pointed out to us by R. Adair and H. Kasha, and others.

Experimental determination of the proper errors is done by measuring the spread in the distribution of the drop count on a number of tracks. Cowan,[10] using an Ar-He mixture of 100 cm Hg found that the experimental error was 1.7 times the error based on assuming statistical independence for each drop, which would correspond to about 3 drops per primary interaction. Kepler et al.,[7] using an argon cloud chamber operated at about 0.3 atm, found the standard deviations for single 40-cm tracks to be 13% with drop counts of 924 or about 4 times what would be expected assuming statistical independence of the drops, and about twice that based on the number of primary ionizing collisions. The errors were large in this case because of the slow growth of the

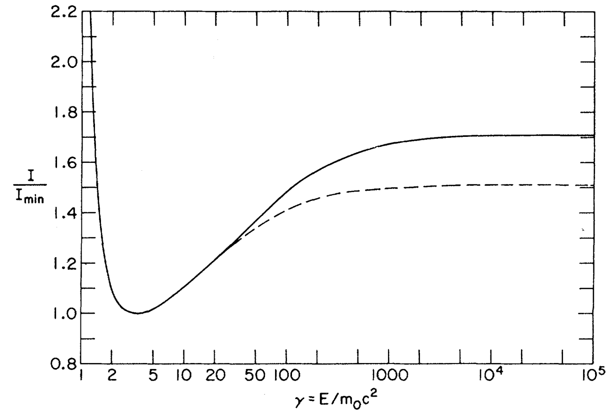

FIG. 1. The restricted energy loss $I = -(dE/dx)_{W_0}$ divided by $I_{\min}$, as obtained from Eq. (1) for pure argon at 1.4 atm and $W_0 = 500$ eV (solid curve). The ratio $I/I_{\min}$ is plotted against $\gamma = E/m_0c^2$ of the incident particle. The dashed curve gives the modified values of $I/I_{\min}$, as explained in the text.

drops in argon without helium and the resultant difficulty in obtaining good pictures of individual drops. They found, in reasonable agreement with the expected restricted energy loss and the measured condensation efficiency, an average of 34 drops/cm for tracks near the plateau of ionization. They eliminated delta-ray blobs having 40 drops or more. At the pressure used by the Sydney group, 160 drops/cm would be expected, or 3200 on a 20-cm track; while they had a count of 330. At 160 drops/cm there would be serious problems due to overlapping droplets. Their quoted errors assume that each count corresponds to an independent event. The method used by the Sydney group gives a count $\frac{1}{10}$ that of the number of drops expected and $\frac{1}{3}$ that expected from the number of primary collisions. In order to establish that their count is an unbiased sampling of the number of primary collisions, and to verify errors, experiments using particles of known ionization would be required.

Sources of minimum particles. –There are at least two significant sources of particles with γ between 2 and 10 (these would have an ionization between 1.0 and 1.1 times minimum): (1) random arrival of muons during the sensitive time of the chamber, and (2) electrons, muons, and hadrons present in the extended air showers that triggered their apparatus.

(1) The Sydney group ran their chamber with a 100-msec delay between the trigger and the signal to start the expansion, and thus the total time available for the ions to diffuse before the droplets grew large enough to stop diffusion would be about 120 msec. They discriminate against late arrivals by measuring diffusion widths (which are proportional to $t^{1/2}$); so we can take as a sensitive time for random events about 20 msec, giving a difference in widths of 8 %, which is within their errors. There were four chambers of average area 120 cm^2, one chamber unshielded and three under 15 cm of lead. Integration over the vertical momentum spectrum[11] of isolated cosmic-ray muons at sea level for 0.17 GeV/$c \leq p \leq$ 1.0 GeV/c gives 2.2×10^{-3} muons cm^{-2} sec^{-1} sr^{-1}, or 28 % of all the muons. We take the zenith angle variation as $\cos^2\theta$ and include only those arriving within 15° of the vertical. Putting these factors together for the 5000 expansions made by the Sydney group, we expect about 7 particles in the unshielded chamber and, taking into account the energy loss in the 15 cm of lead, about 6 particles for each of the other chambers, or a total of 25 muons during the course of their experiment.

(2) A shower is usually initiated by one high-energy hadron which retains much of its energy in each collision and keeps regenerating the electromagnetic and nucleonic cascade down to sea level. The electron spectrum near the core is soft[12] and has been measured above 250 MeV.[13] Below this energy there are only calculations, averaged over the whole shower at maximum development. This spectrum[14] (Table I) agrees in shape and magnitude with the measured spectrum at a distance from the core of 7 m. Since the spectrum goes as the energy times the distance[12] we would expect at a distance of 1.5 m only ~$\frac{1}{4}$ the number of low-energy electrons given by the calculation. Thus we would expect about 1 % of all tracks to be electrons having energies between 4 and 5 MeV.

Electrons are recognized as such in a cloud chamber without a magnet by their multiple scattering or by a single visible kink. McCusker[2] stated that their angular resolution was about 2° (because of the long diffusion time and convection currents in the chamber). The rms projected angular deviation of a 4.5-MeV electron traversing 10 cm of Ar at 1.4 atm is 3.8°[15]; so 40 % of the electrons of this energy would not be recognized by multiple scattering. The probability for no single scattering greater than 2° is 30 %. (Photographs taken with the cloud chamber of Rochester and Butler[16] filled to a pressure of 1.5 atm with a mixture of 80% Ar + 20% O_2, and with a field of 7000 G, show tracks of 5-MeV electrons that are smoothly curved and without visible kinks.) Multiplying the probabilities we conclude that at least 12 % of the 4.5-MeV electrons (1.2×10^{-3} of all tracks) would be straight to within the measurement error and not recognized as electrons.

In this respect it is interesting to note that

Table I. Energy spectrum in air of all the electrons in a shower near the maximum. The numbers are normalized to one electron.

Energy range (MeV)	Relative numbers
<4	0.15
4–5	0.05
5–10	0.10
10–50	0.33
50–250	0.25
250–1000	0.08
>1000	0.04

four of the five candidate tracks occur in the single unshielded chamber and the fifth track in one of the three shielded chambers. The latter has no comparison track in that picture; normalization is on a track in a previous expansion.

At distances of 1.5 m from the core, the measured[17] flux of muons is 1% of the total particles. The muon spectrum is well measured[18] for distances $\geqslant 20$ m and $p \geqslant 1$ GeV/c. The low-energy spectrum near the core has been measured by absorption[19] and indicates that ~25% of all muons are in the range of energies 0.3 to 1.0 GeV. To be conservative, we take the flatter spectrum of Greisen[12,18] extrapolated to 1.5 m and energies <1 BeV which indicates 4% would fall in this range, or 4×10^{-4} of all particles.

The total nuclear active component near the core is 0.5% of all particles.[12] There is usually one, or very few, very high-energy hadrons accompanied by a lower energy hadronic cascade. Estimates[12] indicate that ~70% of all hadrons present have energies between 1 and 10 GeV/c. The roof over the Sydney experiment was about 4 gm/cm^2 or about 1/15 of a collision length. The Kiel group[20] found local showers produced in the wooden beams of their roof. A Sydney group,[21] while calibrating their shower detector, emphasized the large number of low-energy hadrons near the core. We would estimate at least 1/15 of the nuclear-active component would give rise to at least one particle near minimum or 3×10^{-4} of all particles.

Conclusions. —The Sydney group saw about 60 000 particles in the course of their experiment, and from the above we estimate that about 115 of the shower particles would have ionization between 1.0 and 1.1 times minimum. To this we add the 25 random muons. The estimate for the shower particles is for a distance 1.5 m for the core; greater distances would give larger numbers of minimum ionizing particles.

We do not know what the errors of the Sydney group should be, but as mentioned above, a value about twice that based on assuming statistically independent counts would be reasonable. For 1.05 times minimum we would expect for their typical 10-cm track a count of 160 ± 25, requiring only a 2-standard deviation fluctuation to reach the 110 observed.[1] The probability of a variation of this size is about 2%, or 3 tracks from our estimate of 140 tracks. Based on similar considerations, plateau ionizing tracks need to fluctuate by 3.9 standard deviations to reach the Sydney value. The probability for this is 4 $\times10^{-5}$, and operating on the entire sample would yield ~2 tracks.

The large relativistic rise in gasses and the known difficulties in measuring ionization in a cloud chamber make it difficult to establish the existence of $\frac{2}{3}$-charged particles by ionization alone at the level of 1 particle in 10^4. The cores of air showers are indeed good places to look for quarks, but a means for measuring the mass, such as would be provided by a magnetic field or range chamber, would be necessary for a convincing demonstration of the existence of a quark.

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