LETTERS TO NATURE

PHYSICAL SCIENCES

Possible observation of tachyons associated with extensive air showers

SEVERAL searches[1–4] have been made for tachyons using either laboratory particle sources or high energy cosmic rays. Effects associated with their supposed characteristic mass and velocity have been searched for but so far no positive evidence has been reported. As has been repeatedly pointed out, however, the goal of these searches is so important that all possible avenues should be fully investigated. We report here apparently positive results from a pilot search for tachyons associated with cosmic ray showers of energy about 2×10^{15} eV.

The first interaction of a primary cosmic-ray nucleon occurs at a typical altitude of 20 km (ref. 5). Further interactions result in a cascade of relativistic particles travelling with speeds close to that of light (c). Thus, most of the particles in this extensive air shower (EAS) arrive at sea level with a time spread of only a few nanoseconds[6]. If any shower particles are produced with velocities greater than c, they should be observable in the time interval up to 20 km/c (60 μs) before the arrival of the shower front. The precise time depends on their velocity and production altitude. A pilot experiment has been conducted to search for particles arriving within this time period. In this experiment, the EAS which were studied had energies some two orders of magnitude higher than in previously reported work[4].

A plastic scintillator was used to detect the particles. It is not clear what interactions a tachyon might have with the atmosphere or the scintillator. The present search was made assuming that tachyons are produced in EAS interactions at heights between 20 km and 400 m (800 kg m^{-2} and 10,000 kg m^{-2}) and have a sufficiently long absorption length for some to reach the detector. Detection might be accomplished by direct interaction of the tachyons with the scintillator or through the production of secondary particles which interact with the detector. It is not necessary that a single tachyon should produce a large response in the scintillator (as, for instance, a charged relativistic particle would). In principle, provided that observations are initiated by the detection of EAS, it is possible to sum results from many observations so that small non-random effects can be observed.

The chief experimental difficulty with this procedure is that if a recording device is triggered by the arrival of an EAS, it will be too late to observe the tachyon unless substantial signal delays are inserted. This was overcome in the present case by the use of a digital transient recorder (Biomation International, Palo Alto, California; model 610B) which enabled us to trigger our recording system from an EAS and then examine the signal from the particle detector recorded prior to the arrival of the trigger. The device continually samples and digitises (to six bit accuracy) the output of the particle detector. Two hundred and fifty-six words of this digitised data are stored in a shift register which is continually updated. Thus, when a trigger is received, the previous 256 words of data are in store (in our case representing 128 μs) and can be output at leisure. Output was to a chart recorder after digital to analogue conversion. In this mode, the recorder only outputs 228 words (114 μs).

The EAS trigger was obtained from the fast timing part of the air shower array at the Buckland Park field station of the University of Adelaide. Five 1 m square plastic scintillators, 50 mm thick, were used, in a square array of side 30 m, one scintillator being at each corner with one at the centre. Each scintillator was viewed with a Philips XP1040 photomultiplier and the arrival of an EAS was detected by a coincidence between the centre detector and any three of the outer detectors with a resolving time of 150 ns. Thus, air showers were detected from a cone about the zenith, with half angle of about 35°. The mean rate of showers was one per 500 s, corresponding to a minimum shower energy of about 2×10^{15} eV. In addition, one of the corner scintillators was also viewed by an RCA 8055 photomultiplier connected to a charge sensitive preamplifier, the output of which was the signal recorded by the transient recorder. The impulse response of the system had a width of 1.7 μs at half maximum ensuring that a sampling interval of 0.5 μs gave an acceptable reconstruction of the waveform on digital to analogue conversion.

Data from a total of 1,307 air showers, detected between February and August, 1973, have been analysed. The aim of the analysis was to demonstrate whether or not non-random effects were observable immediately preceding an EAS and for this reason a simple analysis procedure was employed. The time (with respect to the arrival of each EAS) of the largest excursion of the amplified photomultiplier output was noted. If there was doubt as to which of a number of pulses was the largest, all the apparently equal pulses were included. In practice, approximately 4% of the events had their two largest pulses sufficiently close in amplitude to cause ambiguity. In order to check on observer bias in assigning relative pulse heights, appoximately 600 events were re-read by an independent chart reader. Some 3% of the events had the assignment of the largest pulse changed but no systematic bias was found.

The position of the shower front on the output trace can be adjusted; thus the time interval available for analysis is dependent on the exact setting of the transient recorder. For 1,176 of the events the record extended beyond 105 μs before the air shower arrival. Figure 1*a* shows a histogram of the positions of the largest pulses for these events. The figure suggests that the distribution of the largest pulses is not uniform and a χ^2 test on the data indicates that there is only 1% chance that the data is from a uniform distribution.

In order to include data from all 1,307 recorded events it is necessary to limit the period of analysis to 97.5 μs before the shower arrival. The resulting histogram is shown in Fig. 1*b*. A χ^2 test on this data shows less than 0.1% probability that the data is from a uniform distribution. In addition, since if tachyons are observed one might expect their arrival times to be spread over more than one 7.5 μs bin, one can also test to see whether there are specific time regions contributing excessively to the non uniformity or whether the large χ^2 is due to a more or less random time distribution of excesses. This problem has been discussed by David[7] who noted that a calculation of χ^2 involved the squaring of deviations from a hypothetical set and that independent information on the sign of the deviations was ignored. An examination of the distribution of bins above and below the mean shows that the probability that our data are selected from a uniform distribution is less than 1%, on the basis of a non-parametric run test.

The data were obtained in 12 runs containing between 70 and 180 events each and the data were tested for the possibility of non-random variations between runs. This was done by comparing data obtained from individual runs with the final distribution. Taking deviations of each bin of each run from the normalised final distribution gave a χ^2 indicating less than a 10% probability that the individual runs were not randomly selected subsets of the total data.

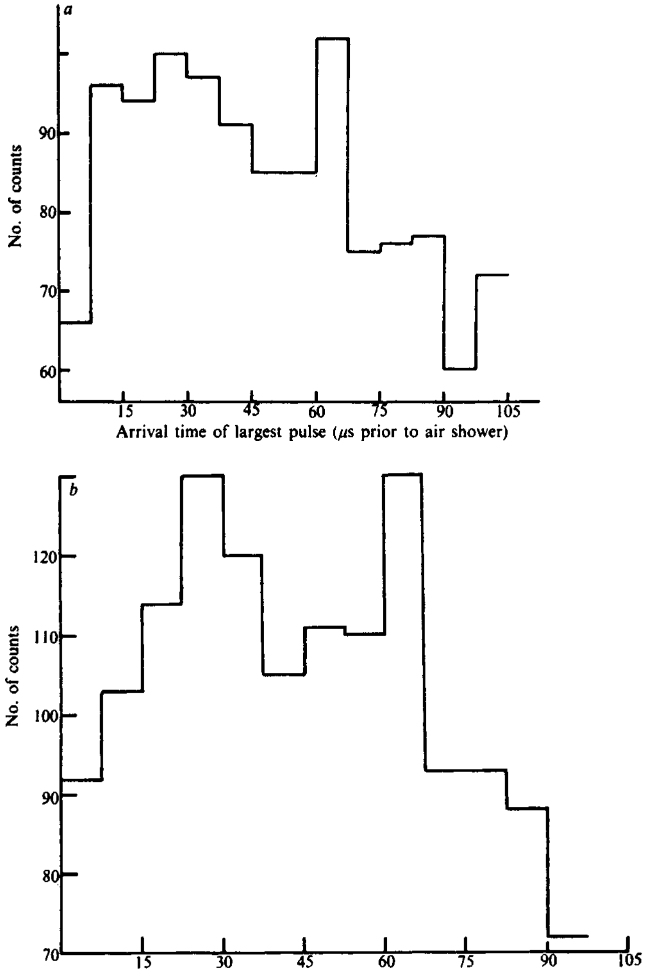

FIG. 1 The time distribution of largest photomultiplier pulse in the period prior to the arrival of an extensive air shower; *a*, data from 1,176 air showers in 14 bins of width 7.5 μs; *b*, data from all 1,307 showers observed in 13 bins of width 7.5 μs.

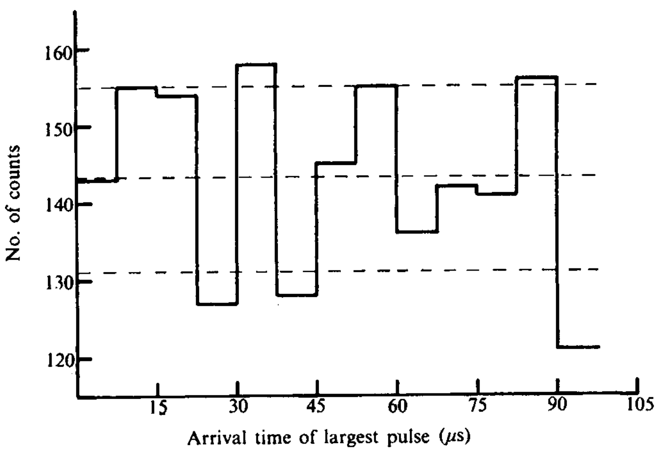

FIG. 2 The time distribution of largest photomultiplier pulses in 1,839 random samples of output in 13 bins of width 7.5 μs.

The experiment has the unique quality that spurious pickup in the electronics is most unlikely to affect the result since pickup must occur at or after the arrival of the shower front, thus arriving after recording and storage of the data. It is arguable that the arrival of an air shower could generate interference in the recorder memory. If this were so, unless only the least significant bit were affected, a discontinuity in the trace would be expected after digital to analogue conversion. In more than 3,000 events no such effect was observed. In addition, grossly overloading the input amplifier with a pulse was found to have no effect on stored data.

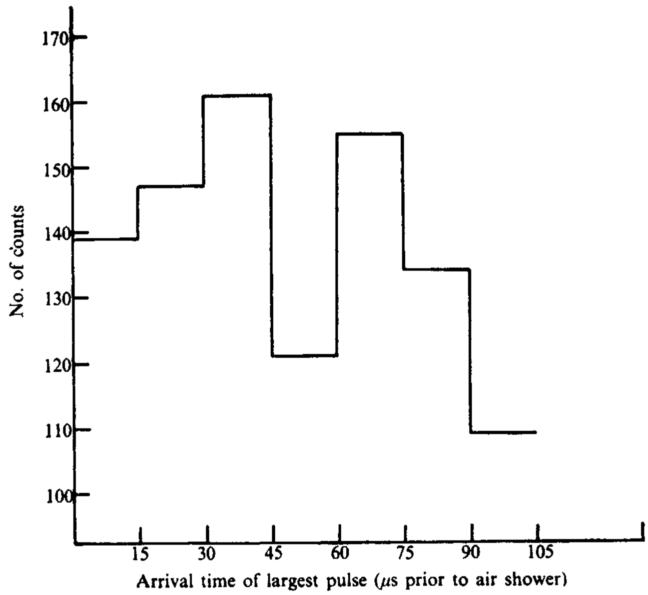

FIG. 3 The time distribution of largest photomultiplier pulses in the 105 μs period prior to 978 extensive air showers. The data was recorded at half the sampling rate of that in Figs 1 and 2 and analysed into 7 bins of width 15 μs.

In case there was some other form of pickup or of observer bias, we have triggered our coincidence system with artificial pulses and repeated the analysis on an apparently random sample of photomultiplier output; 1839 events were analysed in the same way as the air shower triggered data indicating on the basis of a χ^2 test a probability of about 40% that these test results were from a uniform distribution. The data are presented in Fig. 2. The probability that this test data and the EAS data are from the same distribution is less than one in 10^4 on the basis of a χ^2 test.

We have also operated our transient recorder at one half the previous sampling rate (with a lower bandwidth) and taken results over a similar range to that described above. These data from a further 972 showers were analysed into seven coarser bins (15 μs wide) but otherwise a similar analysis technique was employed. The resulting distribution shown in Fig. 3 seems to exhibit the same broad features as Fig. 1. We use this as further evidence that the equipment and analysis technique are largely free from bias since the equipment was now operated in a rather different manner.

Ramana Murthy[4] has reported an unsuccessful search for tachyons in EAS. Two detection techniques were employed, in one of which a liquid scintillator was used and a search made for particles immediately prior to EAS. This experiment is rather similar to the one described above but differs in a number of important respects. In order to avoid the use of long analogue delays, his measurements were initiated by the detection of single charged particles and a search was made for EAS following within 19.2 μs. This technique is much less efficient than ours since only 1 in 250 potential tachyons was followed by an EAS within the time of interest. Also, potential tachyons have the additional constraint that they must produce a response in the scintillator comparable with that produced by a conventional charged particle. As mentioned earlier, the EAS studied by Ramana Murthy were almost two orders of magnitude less energetic than those used by us and also a much smaller time range was examined. Since the peak in our distribution occurs after the 18 μs time interval investigated by Ramana Murthy, the results cannot be directly compared. But a statistical examination of his published data using David's technique indicates that there is less than 5% probability that the data is from a uniform distribution. We note that, subjectively, the observed distribution seems to rise in the period prior to 13 μs before the shower arrival. This is not inconsistent with our observations.

It is possible than an explanation may be found for these results without invoking the existence of tachyons. A. G. Gregory has pointed out to us that fission or spallation in the interstellar medium or production of associated particles at the source might account for the correlated arrival of cosmic rays. We note, however, that unless particles are produced with closely similar rigidity and velocity vectors they are unlikely to remain associated for long in the interstellar or source magnetic fields. A closely related problem has been discussed by Weekes[8] in connection with pulsar periodicities in cosmic-ray arrival times.

We conclude that we have observed non-random events preceding the arrival of an extensive air shower. Being unable to explain this result in a more conventional manner, we suggest that this is the result of a particle travelling with an apparent velocity greater than that of light.

We thank Dr A. G. Gregory and Professors C. A. Hurst and J. R. Prescott for comments, Mr K. W. Morris for advice on statistical analysis, and Ms J. M. Taylor for chart reading. One of us (R.W.C.) holds a Queen Elizabeth Fellowship. The University of Calgary is thanked for the loan of equipment.

ROGER W. CLAY
PHILIP C. CROUCH

Physics Department,
University of Adelaide,
Adelaide, South Australia 5001

Received December 10, 1973.

1 Alväger, T., and Kreisler, M. N., *Phys. Rev.*, **171**, 1357 (1968).
2 Baltay, C., Feinberg, G., Yeh, N., Linsker, R., *Phys. Rev. D.*, **1**, 759 (1970).
3 Danburg, J. S., Kalbfleisch, G. R., Borenstein, S. R., Strand, R. C., VanderBurg, V., Chapman, J. W., Lys, J., *Phys. Rev. D.*, **4**, 53 (1971).
4 Ramana Murthy, P. V., *Lett. Nuovo Cim.* Ser. 2, **1**, 908 (1971).
5 Allan, H. R., *Prog. elem. Part. cosm. Ray Phys.*, **10**, 170 (1971).
6 Bassi, P., Clark, G., and Rossi, B., *Phys. Rev.*, **92**, 441 (1953).
7 David, F. N., *Biometrika*, **34**, 299 (1947).
8 Weekes, T. C., *Nature phys. Sci.*, **223**, 129 (1971).

Black hole explosions?

QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s. The purpose of this letter is to show that this indeed may be the case: it seems that any black hole will create and emit particles such as neutrinos or photons at just the rate that one would expect if the black hole was a body with a temperature of $(\kappa/2\pi)(\hbar/2k) \approx 10^{-6}\ (M_\odot/M)K$ where κ is the surface gravity of the black hole [1]. As a black hole emits this thermal radiation one would expect it to lose mass. This in turn would increase the surface gravity and so increase the rate of emission. The black hole would therefore have a finite life of the order of $10^{71}\ (M_\odot/M)^{-3}$ s. For a black hole of solar mass this is much longer than the age of the Universe. There might, however, be much smaller black holes which were formed by fluctuations in the early Universe[2]. Any such black hole of mass less than 10^{15} g would have evaporated by now. Near the end of its life the rate of emission would be very high and about 10^{30} erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs.

To see how this thermal emission arises, consider (for simplicity) a massless Hermitean scalar field ϕ which obeys the covariant wave equation $\phi_{;ab}g^{ab} = 0$ in an asymptotically flat space time containing a star which collapses to produce a black hole. The Heisenberg operator ϕ can be expressed as

$$\phi = \sum_i \{f_i a_i + \bar{f}_i a_i^+\}$$

where the f_i are a complete orthonormal family of complex valued solutions of the wave equation $f_{i;ab}g^{ab} = 0$ which are asymptotically ingoing and positive frequency—they contain only positive frequencies on past null infinity I^-[3,4,5]. The position-independent operators a_i and a_i^+ are interpreted as annihilation and creation operators respectively for incoming scalar particles. Thus the initial vacuum state, the state containing no incoming scalar particles, is defined by $a_i|0_-\rangle = 0$ for all i. The operator ϕ can also be expressed in terms of solutions which represent outgoing waves and waves crossing the event horizon:

$$\phi = \sum_i \{p_i b_i + \bar{p}_i b_i^+ + q_i c_i + \bar{q}_i c_i^+\}$$

where the p_i are solutions of the wave equation which are zero on the event horizon and are asymptotically outgoing, positive frequency waves (positive frequency on future null infinity I^+) and the q_i are solutions which contain no outgoing component (they are zero on I^+). For the present purposes it is not necessary that the q_i are positive frequency on the horizon even if that could be defined. Because fields of zero rest mass are completely determined by their values on I^-, the p_i and the q_i can be expressed as linear combinations of the f_i and the $\bar{f}_i$:

$$p_i = \sum_j \{\alpha_{ij} f_j + \beta_{ij} \bar{f}_j\} \quad \text{and so on}$$

The β_{ij} will not be zero because the time dependence of the metric during the collapse will cause a certain amount of mixing of positive and negative frequencies. Equating the two expressions for ϕ, one finds that the b_i, which are the annihilation operators for outgoing scalar particles, can be expressed as a linear combination of the ingoing annihilation and creation operators a_i and a_i^+

$$b_i = \sum_j \{\bar{\alpha}_{ij} a_j - \bar{\beta}_{ij} a_j^+\}$$

Thus when there are no incoming particles the expectation value of the number operator $b_i^+ b_i$ of the ith outgoing state is

$$< 0_- \,|b_i^+ b_i|\, 0_- > \; = \sum_j |\beta_{ij}|^2$$

The number of particles created and emitted to infinity in a gravitational collapse can therefore be determined by calculating the coefficients β_{ij}. Consider a simple example in which