Cosmic Schools Group Proposal

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Abstract

The Cosmic Schools Group hope to design affordable Cosmic Ray detection units which can be bought, assembled and run by UK Secondary Schools. These would allow stand-alone experiments to be performed by the students at the schools, e.g. to map the distribution in zenith angle of Cosmic Rays, or to study the effects of demanding coincidences on the observed counting rate, but could also be linked via the Internet to provide one of the world's largest Cosmic Ray detectors. The aim of this first study is to investigate the feasibility of producing such apparatus that is both safe and robust enough for school use for a unit cost of a few hundred pounds, and to do some market research: Are sufficient schools interested in this project to make the mass production of the apparatus a realistic proposition? Are UK companies prepared to sponsor a project such as this, which will help students to acquire many of the skills industry requires? Further, the possibility that this project would allow the construction of a cost-effective Cosmic Ray detector capable of competing with the best existing and planned devices deserves serious consideration.

Motivation

Support for "A" level Particle Physics

Many schools are now teaching Fundamental Particle Physics as part of the "A" level physics syllabus[1]. Currently, there are no practicable experiments that the students taking this option can do. In the opinion of the Cosmic Schools Collaboration, this limits strongly the appeal of the subject. While there are obvious difficulties in rectifying this situation, the average school cannot afford to build and run a particle accelerator, we are fortunate that nature provides us with a source of high energy particles, including the highest energy particles yet observed, in the form of Cosmic Rays. We hope to be able to produce an affordable, safe and robust apparatus that can be run by schools to allow students to experience both the frustrations and the delights of doing physics research and to allow them to see first-hand evidence for some of the phenomena they are discussing in the Particle Physics course. We hope to make this apparatus capable of doing stand-alone experiments, such as identifying the direction of Cosmic Rays and hence mapping their distribution. Further, we hope to make each apparatus capable of forming a component of an extensive air shower array, potentially one of the World's largest, using the Internet and tools such as the World Wide Web to facilitate the collation and analysis of the data taken. We hope that the Cosmic Schools project will give students some insight into the ingenuity, inventiveness and tenacity necessary to design, build and operate a High Energy Physics experiment.

Cosmic Rays and High Energy Physics

The study of Cosmic Rays has been of great significance to the development of High Energy Physics[2], leading to the discovery of the positron[3], the muon[4], the pion[5] and the first strange particles[6]. More recently, Particle Physics has tended to progress primarily through experiments in the more controlled environment available at particle accelerators, but there are indications that the pendulum may be swinging back in favour of Cosmic Rays.

Cosmic Rays are particles which bombard the Earth's atmosphere from space. They are known to have energies which vary from less than 10^6 eV up to more than 10^{20} eV. It is the detection of a handful of events caused by primary particles with energies above 10^{20} eV that has re-vitalised the study of Cosmic Rays. These dozen or so events were recorded by the AGASA[7], Fly's Eye[8], Haverah Park[9], Yukutsk[10] and Volcano Ranch[11] groups.

The Cosmic Ray energy spectrum in the range $10^6 < E < 3 \times 10^{15}$ eV can be described by a power law, $dN/dE \sim E^{-2.65}$. Above this energy range the spectrum steepens, being described by the law $dN/dE \sim E^{-3.1}$ at energies $10^{16} < E < 10^{19}$ eV. The usual explanation offered for this "knee" in the spectrum is that Cosmic Rays with energies less than about 10^{16} eV are confined within the galaxy due to the galactic magnetic fields, whereas those with higher energies are able to escape as the magnetic "lever arm" is not sufficient to trap particles of such high momentum. Cosmic Rays are thought to be largely heavy nuclei at energies below 10^{16} eV, the proportion of light nuclei increasing at an energy of about 3×10^{17} eV[12], though this claim is not supported by all data[13]. Cosmic Rays of all but the highest energies are thought to be accelerated in our galaxy by shock-waves produced in the explosion of type II supernovae.

At energies $E > 10^{19}$ eV up to the highest energies yet observed, $E \sim 3 \times 10^{20}$ eV, the spectrum again flattens out somewhat. The puzzle is, why are Cosmic Rays observed at all in this energy range? If the primary particles involved are protons, as is suggested by the data[14,15] this implies that they are produced locally (cosmically speaking!). The reason for this may be explained as follows. The protons move through a bath of Cosmic Microwave Background

(CMB) photons. If the collisions between these photons and the protons are sufficiently energetic, the photoproduction reaction $\gamma p \to \Delta \to N\pi$ will occur, where N represents a neutron or proton and the charge of the pion must be chosen accordingly. The result of this is that the protons lose a large amount of energy, and this process will continue until their energy drops below the threshold for the above reaction. What is this threshold? In the reference frame of the CMB we can write the proton's four-momentum as $p = (E,0,0,k)$ and that of an average photon as $g = (\varepsilon,0,0,-\varepsilon)$. The squared centre-of-mass energy of the collision is then given by $s = (p+g)^2 = m_p{}^2 + 2(E+k)\varepsilon$. For this to be sufficiently large to allow Δ production we need $s > m_\Delta{}^2$, i.e. $E > (m_\Delta{}^2 - m_p{}^2)/4\varepsilon$, where we have assumed $E \approx k$. Taking the temperature of the CMB to be 3 K (2.73 K is more accurate) and using Boltzmann's constant, $k_B = 8.6 \times 10^{-5}$ eV/K, we get $\varepsilon = 3 \times 10^{-4}$ eV. As $m_\Delta \sim 1.2$ GeV, the necessary proton energy is $E \sim 5 \times 10^{20}$ eV. Here we have used the average photon energy. Allowing for the actual photon energy spectrum causes this limit to drop to 3×10^{19} eV. This energy is referred to as the Greisen-Zatsepin-Kuzmin[16] (GZK) cut-off.

We have shown that protons with energies above 3×10^{19} eV will undergo reactions with the CMB. What remains is to determine the typical distance a proton can travel before suffering such a reaction. This can be deduced from the density of CMB photons, 550 γ/cm^3, and the cross-section for the above reaction, which is 200 μb on the Δ(1236) resonance. The mean free path is thus $\lambda = 1/200 \times 10^{30}\ \mathrm{cm}^2 \times 1/550\ \mathrm{cm}^{-3} = 9 \times 10^{24}\ \mathrm{cm} \approx 3\,\mathrm{Mpc}$. While this distance is large compared to the size of our galactic halo (~ 100 kpc), it is small compared to the size of the local cluster (~ 100 Mpc).

The above suggests that if the highest energy Cosmic Rays are protons, they must be produced within our galaxy. If they are nuclei, similar conclusions may be reached as nuclei start to break up in their collisions with CMB photons at energies similar to the GZK cut-off. It is also possible that the primary particles involved are photons, but these would tend to interact with the photons of the geomagnetic field before entering the earth's atmosphere[17]; the signatures of the observed highest energy Cosmic Rays do not support such an early start of the particle shower. A further possibility is that the Cosmic Rays are neutrinos. This seems unlikely as the highest energy events were observed at incident angles less than 40° from the zenith; the path length for interactions in the atmosphere is too small[18]. Of course, such objections can be avoided if neutrinos interact strongly at very high energies[19], though the phenomenological acceptability of this idea is disputed[20,21]. Another interesting idea, particularly given the recent Super Kamiokande results[22], is that the high energy Cosmic Rays result from energetic neutrinos annihilating on the relic cosmic neutrino background, the neutrinos being assumed to have mass $\mathcal{O}(0.1)$ eV[23]

Assuming that the most energetic primary Cosmic Rays are protons The question then becomes, how can such high energies be produced within our galaxy? The shock-wave mechanism, first suggested by Fermi[24], cannot produce energies above about 10^{19} to 10^{20} eV[25]. Another possibility is acceleration in magnetic fields in the galaxy. The strongest galactic magnetic fields have $B \sim 3 \times 10^{-6}$ G and coherence lengths $L \sim 300$ pc. These could thus accelerate a proton to energies of $eBL \sim \sqrt{4\pi/137} \times 3 \times 10^{-6}\ \mathrm{G} \times 300\,\mathrm{pc} \sim 10^{15}\ \mathrm{eV}$, several orders of magnitude lower than is required.

The above comments on the strength of the galactic magnetic field reveal a further puzzle. The minimum radius of curvature of the path of a proton, charge 1.6×10^{-19} C, with energy 10^{20} eV in a magnetic field of 3×10^{-6} G is 30 kpc, comparable to the radius of the galaxy. We would thus expect the direction of the highest energy Cosmic Rays to reveal the location of their source, but there is no convincing evidence that these Cosmic Rays are associated with any observable features of our galaxy.

A possible solution to both these puzzles is that the highest energy Cosmic Rays result from topological defects which become unstable, producing superheavy gauge and Higgs bosons which then decay to give the required signature[26,27]. These models generally suffer from the problem that the expected flux of high energy Cosmic Rays is too low; an exception being those invoking the topological defects referred to as Cosmic Necklaces[28].

A further possible explanation is that the highest energy Cosmic Rays are caused by the decay of massive, metastable particles that were produced very early in the history of the universe[29]. A detailed study of the possibility that a particular class of particles which arise in the $SU(5)\otimes U(1)$ unification model[30] could be responsible for the high energy Cosmic Rays is presented in[31]. The conclusion is that the so-called cryptons could indeed cause extremely high energy Cosmic Ray protons to hit the earth at approximately the correct rate, if the crypton mass is $\mathcal{O}(10^{21})$ eV.

Thus, we see that Cosmic Rays may once again be providing us with information on Particle Physics at energies beyond those attainable in the laboratory. Interestingly, Cosmic Rays with energies above about 10^{15} eV can only be studied by ground based Cosmic Ray detectors, such as that proposed by the Cosmic Schools Collaboration. These utilise the interactions of the incoming high energy particles with the earth's atmosphere; large arrays of scintillators can be used to detect the shower of particles generated, for example, or the Čerenkov light or luminescence caused by the particle shower may be measured.

The Cosmic Schools Detector

Detector Requirements and Preliminary Design

The detector units for the Cosmic Schools project must be robust, cheap, safe to use and sensitive to the particles to be detected. One obvious choice that may satisfy many of these requirements is a scintillator based detector with wavelength shifter and photodiode or photomultiplier readout. In order to be useful as an element of a large array, the detector should cover an area of about 1 m^2. To fulfil the requirement that it can be used for local tracking it

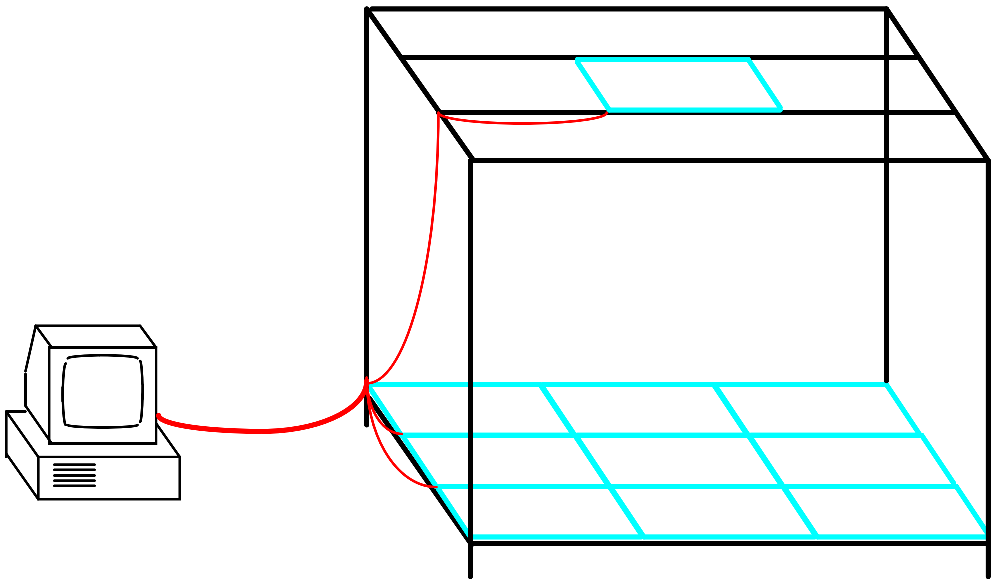

Figure 1
Schematic illustration of apparatus for one element of the cosmic schools collaboration detector.

must also be able to provide directional information; here a "Cosmic Ray telescope" using two scintillators of dimensions perhaps 30 x 30 cm^2, separated by a distance of about two metres, is appropriate. A sketch of a detector that fulfils both these requirements is shown in figure 1. It is composed of ten identical elements. These consist of a sheet of scintillator, to one edge of which is attached a strip of wavelength shifter (WLS). The photodiode or photomultiplier which converts the detected light to an electronic signal is affixed to the end of the WLS. The elements are supported in a "Meccano" frame.

In order to keep the associated electronics as cheap as possible, while providing a high degree of flexibility, we propose to put them on a card that can be inserted into a PC. To remove the need for separate power supplies, again cutting costs, the card should provide the power for the photodiodes or photomultipliers. The electronics should, as a minimum requirement, allow "local" and "global" operation. In local mode, it should be possible to display the singles counts and rates in the individual scintillators, and also allow various coincidence conditions to be required and the resulting count rates displayed. In global mode, the apparatus must be able to record information about the signals observed in the scintillators together with an accurate time-stamp. This data must be stored in such a way that it can be easily down-loaded to a central storage system. To avoid generating too large a quantity of data, the global mode signals should require signals in coincidence from at least two of the scintillators in the array.

Data taking and analysis

The data available in local mode, read from the PC screen, can be analysed easily using pocket calculators, software tools such as the Microsoft Excel package, or simple programs written by the school students. Various questions may be studied, the following serve as examples:

1. Are the observed rates proportional to the area of the scintillators?

2. Can the efficiency of the scintillator and readout systems be determined?

3. How does the rate in the cosmic ray telescope vary as a function of the telescopes orientation?

Fulfilling the requirements of global mode data taking is more difficult. The necessity of adding accurate timing information requires that a precise clock signal be obtained; probably the Global Positioning Satellite (GPS) system is the most suitable source of this signal. Analysis of global mode data also requires that the location of the detector be known. This could either be done automatically, again using the GPS system, or the experiment's software could allow the students to enter the latitude and longitude of the position at which the apparatus is operated.

Central data acquisition

The central data acquisition system must be able to accept data from the array elements as and when they make it available. It should be located at a university, with perhaps several sites keeping copies of the data to ease access and for safety reasons. These central systems should make the data available to schools in a way that allows analysis using the packages commonly found on PCs in schools. In addition, relevant Monte Carlo simulations should be done at the central sites and the results made available over the World Wide Web (WWW).

Feasibility studies

Market Research

Before even the moderate amounts of money the Cosmic Schools project would require are spent, it is sensible to determine how many schools are interested in the idea and how much they would be prepared to pay to buy their array element and join the Cosmic Collaboration.

Technical Problems

There are also technical issues to be resolved. The amount of scintillator necessary for the proposed apparatus already makes it rather expensive, given typical prices. To what extent can costs be reduced by mass production? Is the suggested detector design adequate, i.e. scintillator sheets readout via a wavelength shifter bar and photodiode or photomultiplier, or must more elaborate schemes be used to collect enough of the scintillation light[32]? Certainly, studies must be done on the choice of the type of scintillator, wavelength shifter and photodiode/photomultiplier. Can the required electronics be produced at a reasonable price? How are the problems associated with acquiring the necessary accurate timing information best solved? How can a global mode trigger be realised which results in acceptable data taking rates and reasonable efficiency?

Sponsorship

A further issue is that of sponsorship; are UK companies interested in sponsoring this project, which will help students to develop many skills useful to industry? In particular, would manufacturers and suppliers of PCs be interested in subsidising the schools to purchase, for example, PCs that could be used for this project, but also for other purposes within the schools?

Future Programme

The above outlines some initial ideas on what we feel to be an exciting project for all involved, and also some of the problems that must be solved before the project can be realised. Our hope is that we can develop the necessary apparatus in the next two to three years. This we would like to do in the context of a pilot project run with a group of Merseyside and Lancashire schools. Initially we will apply for funding at the level of a few thousand pounds through the UK Particle Physics and Astronomy Research Council (PPARC) Small Awards Scheme for Projects in Public Understanding of Science. This money will be used to purchase scintillator, wavelength shifter, photodiodes, photomultipliers, power supplies and electronics to enable us to study various possible designs for the Cosmic Schools detector. The testing of scintillator, wavelength shifter and photodiode/photomultiplier combinations will be done at Preston College and Liverpool University. Students will be involved in the testing throughout, enabling us to form an early impression of the suitability of the apparatus for use in the school environment. In parallel with these tests, preliminary design work on the electronics necessary to supply power to the detectors and perform the readout using a PC will be done at Liverpool University, one of the major problems being that of integrating the precise clock signal into the readout. The aim of the group is to have , at the end of the second year, a preliminary design for the complete detector. We will then apply for further funding, perhaps through the same scheme but perhaps also for a larger amount through the PPARC National Awards Scheme, to enable us to build several detectors and install them in Preston College and schools around Merseyside. This will allow us to iron out the inevitable teething problems with the detectors and to study the possibility of linking the detectors to form an Extensive Air Shower array. Simultaneously, we will investigate sponsorship possibilities and start to publicise the pilot project in schools. Once all problems have been solved we would then hope to extend the project to cover all schools in the UK.

Summary

The Cosmic Schools Group aim to develop robust and safe apparatus that will enable “A” level physics students to perform Cosmic Ray experiments in their schools. The apparatus will be so designed that the data from each individual school’s apparatus can be stored locally using a PC and then collated via the Internet, allowing the study of Extensive Air Showers. If enough schools are interested in this project, it could result in the creation of the world’s largest Cosmic Ray detector, albeit a fairly “sparse” one. This would allow the study of extremely high energy Cosmic Ray events and the search for some novel new phenomena, for example for events arising from the interaction of highly energetic as yet unidentified particles in the material of the earth, resulting in the production of extremely large area showers at the Earth’s surface. It is also possible that similar exotic events occur in the material of the moon.

If the project catches the imagination of enough people, it may be possible to extend it into Europe, perhaps attracting European Union finance.

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