1.1 Experiments with a cosmic ray telescope.

Name of your Institution: University of Birmingham

Title of the educational scenario template: Inquiry-based teaching

Title of your educational scenario: Detecting cosmic rays with scintillation counters

Educational problem:

In our everyday experience, we are oblivious to the cosmic rays passing through our homes and our bodies. These particles, mainly from outer space, are detectable only via their interactions; charged particles leave trails of ionisation and neutral particles pass through matter causing no effect until they interact to produce charged particles which are then detected via their ionisation. Despite this apparent intangibility, charged particles can be detected in plastic scintillation counters and we can then determine basic characteristics of these cosmic rays. We can investigate phenomena which seem at first sight beyond our reach.

Educational scenario objectives:

During the scenario, participants will:

1. investigate the origin of cosmic rays (primary cosmic rays)
2. will realise that the primary cosmic rays interact high in the Earth's atmosphere producing showers of secondary particles
3. appreciate that these secondary cosmic rays comprise mainly muons (200 times heavier than the electron and with a lifetime of just over $2\mu s$)
4. understand how charged particles interact as they pass through matter, in particular how they may be detected by the trails of ionisation which they produce
5. discuss how these trails of ionisation, constituting tiny amounts of electrical charge, may be detected
6. understand how a charged particle may be detected by using a scintillation counter i.e. a scintillator and photomultiplier tube combined.
7. convince themselves of the basic principles of electronic detection: although most signals from the photomultiplier tubes comprise noise pulses, one can detect particles by demanding a coincidence of two or more scintillation counters.

8. using several scintillation counters, set up a cosmic ray telescope and measure the rate of incident cosmic rays
9. with the counters mounted vertically one above another, determine how the measured rate varies with the separation of the counters. How precisely can one define the direction of the incoming particles?
10. with the counters lying in a plane, measure the coincidence rate and determine how the rate changes as the horizontal separation of the counters increases
11. devise a programme of experiments e.g. repeat the measurements at different times of the day, indoors and outdoors, in different parts of the building
12. look for correlations of the measured rate with external factors like air temperature and pressure
13. by measuring delayed coincidences between counters in a vertical stack, determine the muon lifetime.
14. discuss how these measurements agree (or not) with the known properties of cosmic rays
15. summarise their data, describe to other groups what they have done and, if possible, compare results
16. understand the connection between their cosmic ray studies and current particle physics experiments

Characteristics and needs of students:

In their early studies, particle physics (and to a lesser extent astronomy) seem very remote to students. The particles are produced apparently mysteriously in interactions at high energies; most are unstable and decay before travelling a significant distance; those particles which do not instantly decay are observed only indirectly. The particles are too small to be seen directly. By presenting students with a scintillation telescope and encouraging them to devise their own experiments, they can begin to appreciate how we can probe this sub-atomic world.

Students may be familiar with alpha, beta and gamma radiation and with possible sources of such radiation but may be less familiar with another source of background radiation – cosmic rays. This flux of particles from outer space (typically one a second through their heads) is intriguing. Students quickly surmise that the reason they are not aware of these particles is that they are so small that they pass through their bodies without interacting. But if they produce no effect, how can they be detected? If detectable, might these particles have some impact on their bodies? Such questions immediately spark students' interest.

By using scintillation counters students will understand how the devices operate, will appreciate the difference between signal and noise and how to suppress the latter – apparently esoteric concepts but quite straightforward when one can access the equipment directly. They can alter the setup of the scintillation counters to follow their own programme of measurements. Results will be analysed and discussed and then the next steps agreed. Competence in these techniques will stand the students in good stead in later years.

At each stage, the students will describe what they have done, discuss the relevance of what they have observed and agree how to proceed. Communication is essential in research and these activities will illustrate this well to the students. Comparing their results with existing data will allow students to access published data and appreciate the importance of estimating uncertainties and of noting carefully the exact conditions of their measurements. Having seen how their own simple setup can produce significant results, students will appreciate the importance of much larger cosmic ray experiments (e.g. TRACER, KASCADE, Auger, HESS and CTA).

http://tracer.uchicago.edu/

http://www-ik.fzk.de/KASCADE/KASCADE_welcome_Grande.html

http://www.auger.org/

http://www.mpi-hd.mpg.de/hfm/HESS/

http://www.cta-observatory.org/

Rationale of the Educational approach and Parameters guaranteeing its implementation:

This scenario allows students to gain experience in working with real particle detectors enabling them to design their own experiments and to compare their results directly with existing data. Although the students do not construct the detectors themselves, they do gain hands on experience with the equipment, altering the physical setup of the counters, determining the optimal HV operating points of the photomultiplier tubes and measuring rates from the counters, individually and in coincidence. We believe that the practical experience of interacting with the apparatus is key to students' understanding and establishes a level of confidence which will allow them to devise their own original experiments.

Although a teacher will be at hand to offer advice, the students will determine after discussion how best to proceed with their investigations. Since some students will prefer to work directly with the detectors while others will enjoy more investigating details on the web, the teacher can gently steer their activities so that students become aware of all parts of the experimental work and are adept in all aspects.

The investigations will raise issues which will attract the students into unexplored areas of physics. For example the fact that the principal component of secondary cosmic rays consists of muons is a direct illustration of time dilation and of the importance of Special Relativity. (As the muon has a lifetime of $2.2\mu s$, it will travel on average $660m$ before decaying, even if moving at the speed of light . Hence there is a negligible chance of a muon surviving from its point of production in the upper atmosphere to the surface of the Earth...... unless one invokes Special Relativity!).

Learning activities:

Phase 1: Question Eliciting activities

As an introduction to see the connection between cosmic rays and astrophysics and particle physics, see : http://www.bbc.co.uk/news/science-environment-19152741

Discussions, led by the teacher or leader, on the following topics

- what forms of radiation are we familiar with? (*light from the Sun; alpha, beta and gamma rays; cosmic rays (?)*)
- what are cosmic rays and where do they come from? (*charged particles, mainly protons; low energy particles from the Sun; higher energy mainly from exploding stars; highest energy from massive black holes ??*)
- what happens when a charged particle passes through matter? (*ionisation)*
- how to detect this weak trail of ionisation? (*droplets in vapour -> cloud chamber; bubbles in boiling liquid -> bubble chamber; sparks along ionised trail -> spark chamber; flash of light in scintillator-> electrical signal produced by a photomultiplier tube*)
- what properties of cosmic rays might be measured with a set of scintillation counters? (*direction – how precisely and how might that be improved,*?*; simultaneous arrival of several particles – by setting several counters side by side*)
- discussion of particle decay and querying what rules might govern these decays (*the concept of energetic states decaying to states of less energy can be developed and the various conservation laws introduced, opening the door into particle physics*).

Phase 2: Active investigation

Critical investigations on the following topics

- how are charged particles detected by scintillation counters? (*ionisation-> flash of light in scintillator; optical photons scatter mainly via total internal reflection into pm tube -> photons knock electrons out of photocathode -> electrons avalanche in pm tube -> measurable pulse of charge*)

- what is the expected flux of cosmic rays? (*typically* $1m^{-2}s^{-1}$*; how must this number be modified to take into account the angular range accepted by the counter telescope; introduction of the concept of solid angle*)
- to what extent do cosmic rays appear as single particles or as showers of particles? (*compare rates with counters stacked vertically and laid out horizontally*)
- measurement of the muon lifetime (by measuring the differences in time between a muon stopping in scintillator and the instant of its decay to an electron, plus neutrinos, its lifetime can be determined).

Phase 3: Creation

The students use the cosmic ray telescope and at each stage compare results with expectations. The cosmic ray telescope is described and a summary of possible activities is given in:

http://www.ep.ph.bham.ac.uk/twiki/bin/view/General/QuarkNet

Setting up and details of possible experiments are described in :

http://www.ep.ph.bham.ac.uk/twiki/bin/view/General/WorkSheets

- initially follow the exercises described in the Worksheets
- discuss together at each stage what to do
- note down equipment settings and measured rates. (*Rates can be measured directly on a scaler or recorded automatically by a PC*)

Phase 4: Discussion

Students describe their data to each other and analyse critically their findings.

- Do your experimental results agree with expectations? (For example, if the flux of cosmic rays was measured as a function of angle, time, height, air pressure etc, do these measurements agree **qualitatively** with what we expect from the initial study of cosmic rays)
- Then the interesting dialogue begins: what are the uncertainties involved in measurement and in the prediction? Are the two consistent **quantitatively**?
- Are results compatible with those taken by other groups locally and internationally (whether published or presented on web sites)

Phase 5: Reflection

Students appreciate the implication of their results and begin to see a connection with scientific research. This is the key element of research: scientific progress being made by comparing experiment with theory looking for consistency or shortcomings).

- Do results suggest that our picture of cosmic rays (i.e. their origin and production) is correct?
- Might the standard picture have to be modified? Is there any supporting evidence for such move?
- The cosmic rays observed in the scintillation telescope may be produced as part of *extensive air showers*, being studied, for example, in the Auger project in Argentina:

http://www.auger.org/

Participating roles:

Students

- Gain experience in using particle detectors
- Become familiar with data taking, judging how long to run and when to change conditions
- Assess uncertainties (both statistical and systematic)
- Estimate what results are to be expected and compare with measurements
- Consider the implications of their results. Do their measurements agree with those of other groups? (*Check via the website above*).
- Produce a poster summarising results. This can then be used to describe the activity to other groups.

Teacher

- Explains the basic principles of particle detection

- Advises how the scintillation counters work
- Guides the students' laboratory work via the worksheets
- Activates discussion and encourages students to follow their own original lines of enquiry
- Suggests parallel investigations on the WWW in order to cross-check results
- Helps the students in evaluating their results
- Guides the student to refer to research papers where similar data were taken
- Allows students to repeat measurements if necessary (i.e. enables a very open-ended investigation)

Tools, services and resources:

Part of a room or laboratory in which to use the scintillator telescope.

The cosmic ray telescope comprises a set of scintillations counters, whose signals are read out by a Quarknet electronics board which stores the data and allows analysis of the signals to be accomplished simply by connecting the Quarknet board to a PC or laptop

http://quarknet.fnal.gov/

The Quarknet board is equipped to read out GPS signals which allows timing and location information to be recorded automatically. The website above points to the Cosmic Ray e-lab which contains a wealth of ideas and tools with which to analyse data. For example:

http://www.i2u2.org/elab/cosmic/home/project.jsp

The scintillation counter consist of a plastic scintillator connected to a photomultiplier tube (pmt) which is maintained at its operating high voltage by means of an LV control voltage. Therefore the counters are completely safe to use and there is no danger from HV. (The construction of the counters is described in the above reference).

The apparatus, comprising the telescope and Quarknet board, may be borrowed from University of Birmingham:

http://www.ep.ph.bham.ac.uk/twiki/bin/view/General/QuarkNet

Other research groups (for example at the University of Dresden in Germany) support a very similar scheme.

PCs with Internet access.

A whiteboard on which discussions can be based, estimates can be made and results described.