High Energy Physics on a Lunar Base.

Contribution to the 1991 ESA study.

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Abstract

High energy physics on the moon is restricted to cosmic-ray related studies. Some important topical questions in cosmic-ray research are reviewed and the specific interest of experimentation on the moon is assessed. Cosmic rays provide information on particle interactions at extreme energy. At lower energies, they are at the origin of embarrassing background for specific particle physics studies. Whilst they still raise challenging questions about their origins, they give important pieces of information in astrophysics. The moon and the earth offer quite different conditions, which have both unique advantages. Nevertheless, the earth offers still unexploited possibilities, which are likely to attract most of the available resources in that field, for some time to come.

1-Introduction.

The earth is bombarded by high energy particles and experimentation in high energy physics, originated with such cosmic rays. Cosmic rays were discovered in 1913 by V. Hess. They are usually associated with showers of particles which are produced in the atmosphere by energetic primaries. This typically corresponds to a long series of cascading processes [1]. Cosmic rays for a long time provided the only available source of particles with energy in the excess of 1 GeV. From the thirties to the fifties, they were the highly fruitful hunting grounds for new particles ! Whilst experimentation with high energy particles definitely moved to

accelerators in the mid-fifties, cosmic rays have remained the object of some considerable research. Indeed, the mechanisms at the origin of cosmic ray primaries still raise challenging questions. The nature and the properties of the sources of these primaries still demand important studies which look the more so interesting that specific new features, such as localised sources of very high energy particles, have been discovered [1,2]. The physics of such intense "point" sources, in the TeV range and above, offers fascinating challenges.

At the same time, advances with detectors have pushed the exploration of the high energy part of the spectrum much beyond the maximum energy available with present accelerators. Cosmic ray particles of up to 10^{12} GeV have been seen [3]. This corresponds to a beam energy of the order of 10^6 GeV for a proton-proton collider ! This is two orders of magnitude above the potential of the machines which will be available only at the end of this decade, whilst, with 10^6 GeV cosmic rays, we are at the level of present colliders. Fluxes are, however, low. The integral incident flux, including incident particles above a particular energy $E(\text{GeV})$, corresponds to a rate of $(E/10^{10})^{-2} \text{ Km}^{-2}\text{year}^{-1}$. For 10^8 GeV, for instance, this implies about one event per Km^2 per hour. This is rather low! With the SSC (LHC), collisions at the same centre-of-mass energy will occur at a rate of 10^8 per second. Low fluxes notwithstanding, such extremely high energy particles remain very valuable tools to venture a first exploration of high energy phenomena to still higher energies than those which will be available with the coming generation of colliders [4]. Indeed, in the recent past, cosmic ray results have been quite useful to anticipate what typical events at the present colliders would look like [5]. This corresponded to primary energies of typically 10^5 to 10^6 GeV. There are even a few peculiar events reported in this energy range, which still call for an interpretation, such as the Centauro events [6]. Nothing like them was found in p-pbar collisions. In retrospect, considering the crop of results which came from the CERN p-pbar collider [7], one may say that cosmic rays provided but a small glimpse of what was found. Yet, they came first with a few hints.

The links between astrophysics and particle physics have become very numerous and fruitful. The observation of the neutrino burst from SN 87 A, with all the information which it provided, both on supernova dynamics and neutrino properties, has been a particularly dramatic example of such a many facet connection [8]. More generally, many questions associated with cosmology are addressed in terms of particle physics and huge underground detectors are searching for cosmic neutrinos and for effects due to

hitherto unknown particles [1,8,9].

As is well known, the signal of today quickly becomes the background of tomorrow. There are experiments for which the cosmic ray background raises serious problems. This is in particular the case for the cosmic neutrino background from which we cannot screen ourselves going deep underground. The present limit on the proton lifetime is such that this neutrino background presents us with a serious problem [10]. It has to be dealt with better than presently done, in order to reach much beyond the present limit, which is of the order of 10^{32} years.

This is with these questions in mind, which all bear witness to the thriving aspects of this field of research, that we can approach experimentation on the moon. It is clear that experimentation on the moon would offer some specific advantages, and even great opportunities, that we shall try to itemized. If a lunar base would be available, and if it would be possible to deliver there bulky equipment at an acceptable cost, it is clear that some particle and cosmic ray physicists would love to use it. However, as we shall see, most of the challenging questions correspond to present limitations which are due to rate far more than to background. The conclusion is then that, even if the moon can offer a direct observation of primaries and much better background conditions, most of the problems can most probably be more efficiently addressed on the earth. The case becomes overwhelming when one takes into account the fact that there is a factor of 4 to 5 orders of magnitude in delivery costs, when it come to the sophisticated parts of the detector which have to be constructed in the home laboratory! We are also at a time when very high energy cosmic ray research is changing gear. Ambitious detectors originating from particle physics research are now being substituted for the relatively simple devices long used in cosmic ray studies [1,8,9]. The prevailing attitude is that a high return investment can be made with the development of large sophisticated earth-based detectors, and that diverting a significant fraction of the available funding for a much less ambitious work based on the moon would not look promising. Whilst one meets enthusiastic individuals when discussing moon-based cosmic ray studies, the fair assessment is that the overwhelming majority is for the extension of earth-based studies, which have just entered a new era.

The typical time scale for big equipment on the earth is of the order of 10 years. It is only a factor two down as compared to the likely time scale for the first permanent scientific exploitation of a moon base! It is therefore not natural to try to fully dissociate the physics from the funding.

This being said, one can still address the question with an open mind, since we are considering long-range plans anyway. The purpose of this note is to survey topical questions in cosmic ray research trying both to be general in view of the time scale involved for any project, but also to specify those questions where research on the moon would eventually offer specific advantages. The question of proton decay [10], for which the moon could indeed present a unique opportunity, but for which the bulky nature of the needed detector and its underground installation, should involve a still longer time scale, will be addressed in a separate section.

We shall concentrate on physics issues and not on experimental techniques which could be used on the moon. It is clear that when such experimental possibilities arise, the available detectors will be far more ingenious and powerful than those which can be conceived today.

There are three main questions to address, and, presenting them, we already announce the general conclusions.

(i) What is the nature and origin of very high energy cosmic rays ?

This is an astrophysics question. The key problem in addressing it experimentally is rate, and the answer is therefore in the size and instrumentation of the detectors. The earth wins over the moon, unless there are challenging questions associated with the composition of the primary flux at very high energy. There are no burning question now. Some may come however from results from satellite studies, done first at lower primary energies.

(ii) Are there stable hitherto unknown particles ?

Many names have been pronounced! Aknowledged objects, but often of unknown nature since there is more dark matter than bright matter, correspond to less than 20% of the critical density, which many theorists would like to find. This is both an astrophysics and a particle physics question since one would then have to understand the nature and production of such new objects and this may lead us to the high energy conditions of the Big Bang. Here again, one should first wait for more information from earth-based and satellite studies. There is no reason why such remnants should not be within the galaxy. They should then be even more abundant at lower primary energies. In this case, the moon (or satellites) wins over the earth if cross sections are appreciable, since direct access to the primary is needed. This is in particular the case for mono-energetic gamma rays which could signal the pair annihilation of hitherto unknown particles.

Searches in moon rocks, such as looking for possible evidence for

monopoles, will continue, but this will take place in a natural way, on the sideline.

(iii) Are there surprises in store at extreme energies ?

This is a high energy physics question. We expect some but we need preconceived ideas in order to assess the potential of specific experimental conditions. As an example, we may consider scenarios in which the electroweak interaction could show spectacular behaviours at very high energy. We shall later discuss a particular one in connection with Cygnus X-3 [2,11]. We here mention the possibility that a strong interaction behaviour, with geometrical absorption, could affect the cloud of weak gauge bosons carried along by quarks and leptons [12]. This has to do with the infrared behaviour of non-abelian gauge theories at high temperature. High W densities in very high energy collisions could provide the specific conditions required. The energy threshold, connected to the W mass, is expected to be of the order of a few TeV in the centre-of-mass. The cross section, also related to the W mass, would be of the order of a nanobarn to a microbarn. Such events would be spectacular, with an abundant production of gauge bosons, Higgs particles and leptons, with transverse momenta of tens of GeV, related to the short range nature of the interaction [12]. A high energy behaviour of that type is speculative. Yet, such events are worth looking for! They could be missed with the coming generation of colliders because of their high energy threshold. Could cosmic rays offer the only way to look, for quite some time ?

One should remark that, in all these scenarios, the present one being presented as a particularly striking example, quarks and leptons are affected the same way since it is the electroweak interaction which displays totally new features at very high energy. Neutrinos should therefore show such a spectacular behaviour and, for them, it would be the only important interaction when traversing dense matter. We expect cosmic neutrinos to be abundant and, for them, even with such cross sections, the atmosphere would still remain almost transparent. Indeed, 1000 g/cm^2 corresponds to one mean free path for a cross section of 3 millibarn. In such a case, experimentation on the earth wins.

The new challenging and speculative questions will certainly be different 20 years from now, after we have explored the TeV range at the constituent level [4]! One may however venture the prediction that anything really peculiar at extreme energy, where cosmic rays could reach beyond the existing colliders of that time albeit with very low fluxes, should involve a new important and short-range interaction of the neutrino. The

earth would then remain the winner. Purely high energy physics on the moon brings us back mainly to proton decay, which we shall discuss later.

The electroweak theory is both simple and beautiful. Yet it uses a rather complicated vacuum. The vacuum behaves as a medium and shows similarities with a superconductor. The Glashow-Salam-Weinberg theory of the electroweak interaction can be considered as a relativistic and non-Abelian extension of the Landau-Ginsburg theory of superconductivity. The critical temperature would then be of the order of 200 GeV. Peculiar effects should occur when the collision energy much exceeds such a value, and, more specifically, when it is greater than one TeV at the constituent level. This is what sets the scale for the energy of the SSC(LHC) [4]. Neutrino interactions at very high energy is therefore a promising hunting ground.

The rest of this paper is organized as follows. In section 2, we survey the cosmic ray spectrum and the topical questions raised by its study. In section 3, we compare earth-based to moon-based experimentation in more detail than done so far. This corresponds mainly to astrophysics studies. Section 4 brings a discussion of the relative advantages of a moon based detector for proton decay.

Whilst sections 2,3 and 4 develop the different points already mentioned, the main conclusion is already clear from this extensive introduction. Section 5 explains why we do not consider the construction of research accelerators on the moon. The conclusions are summarized in section 6.

The moon will certainly be used as a base for cosmic ray studies and some particle physics studies when it is accessible at an acceptable cost. At present, however, earth based and satellite equipments offer the best tools to address the topical challenging questions in these fields of research. There is no pressing need to make any major experiment on the moon in view of the promising earth-based projects which one wishes to push forward first. However, some limited experiments will probably be done at an early stage, in the wake of other projects for which a moon base offers some unique opportunities.

2-A survey of the cosmic ray spectrum.

Cosmic rays correspond to stable particles entering the atmosphere at very high energy [1]. The relative majority corresponds to protons. However, up to 1 TeV, where much data exist, the fraction of medium and heavy nuclei increases with primary energy. The proton abundance up to 1

TeV is of the order of 40% , with about 20% for alpha particles, and 10% for iron. Above 1 GeV, all rates fall almost as sharply with energy and primary protons thus retain an overwhelming role when one considers the incident rates in terms of the energy per nucleon. The very high energy spectrum is shown in figure 1. The integral rate per m^2 hour and steradian is given as a function of the energy of the primary, E , in GeV. The spectrum is to a first approximation falling as an inverse power, E^{-x} , but shows two kinks. The first one, which is quite noticeable, corresponds to a change in the exponent x from 1.7 to 2.1. The second one, which is not as clear, is associated with a change of the exponent from 2.1 to 1.8. Whilst the first kink could have also to do with a change of composition, both kinks seem to correspond to the effects of the magnetic galactic field, trapping lower energy particles and permitting the penetration into the galaxy of extremely energetic particles only. If we consider a primary of 10^6 GeV, say, we are at the level of one event per day for a surface of 10 m^2 . This is TeV physics in terms of colliders, where we are today.

The composition is known up to 10^5 GeV from detectors at various depths in the atmosphere [13]. The composition changes but does not show any wild variation with energy. Up to 10^6 GeV, cosmic ray events can be studied with emulsion stacks of reasonable sizes. Above that energy, rates are such that one has mainly to rely on extensive air showers, collecting some of the many secondaries associated with the initial collision in the atmosphere and the following cascades. They may cover an extensive area. At sea level, a proton of 10^6 GeV, impinging on the top of the atmosphere, results in typically 10^5 particles, scattered over several thousands of m^2 .

Up to 10^9 GeV, cosmic rays appear to originate almost isotropically from space. As the recorded energy increases beyond 10^{10} GeV, some maximum may appear in the direction of the "near-by" Virgo cluster, but this is still under debate.

Hadron primaries produce a large number of π mesons which give muons before they are absorbed. Showers are therefore muon rich. There are, however, showers which are muon poor and which are then naturally associated with incident photons. A photon will indeed originate a cascade where, at each step of photon fragmentation, the relative abundance of charged particle correspond typically to the inverse mass square, as implied by the Bethe-Heitler formula. In such photon showers, higher mass particles are mainly photoproduced. In quantitative terms, the relative probability for the formation of a muon and electron pairs is of the order of 10^{-5} . The relative probability of pion photoproduction and electron pair formation in the atmosphere is of the order of 10^{-3} .

Photons are particularly interesting since they are not deviated by the galactic magnetic fields as charged particles are in an important way. Their direction reflects that of the source, whilst the directional origin of even very high energy charged particles, in the 1000 TeV range, is smeared away. Photon primaries are therefore the particles to use when looking for point sources.

One of the prominent findings was the discovery of such point sources. The most intense ones are typically galactic X-ray binaries [2,9,11]. One may quote in particular, among the different sources which have been identified, Cygnus X-3, which is about 10 Kpc away, and Hercules X-1, at about 5 Kpc. Such sources produce very high energy photons over a wide energy range (from 1 to 10^7 GeV, say). The photon flux at 1 TeV corresponds to $5 \cdot 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, for Cygnus X-3, and to $3 \cdot 10^{-11}$ for Hercules X-1. Such very high energy photons also originate from the Crab nebula but its relevant luminosity is a hundred times lower than that of Cygnus X-3. These sources of very high energy photons are fantastic tools to study some of the mechanisms at the origin of cosmic rays. Photons can originate from electrons or from π^0 decay. In the latter case, charged pions should also give neutrinos and the observation of such very high energy neutrinos becomes a great challenge. The dependence on the production conditions of the neutrino to photon ratio makes it a very important parameter to measure. An a priori reasonable estimate gives 50 neutrino events per year from Cygnus X-3 for a 1 Megaton detector, but this assumes a steady source. To be more specific one may venture a rate of $10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$ for this neutrino flux at 1 TeV. Present detectors could reach only up to 10^{-7} .

More generally speaking, the neutrino to hadron ratio in the high energy part of the cosmic ray spectrum is a very important parameter. It would tell us how pions can survive in the production zone and therefore probe the density. The rise of the neutrino cross section with energy, due to the short range of the interaction, makes the detection of such very energetic neutrinos easier than for those of lower energies. The cross-section increases indeed by 5 orders of magnitude between 10 and 10^9 GeV! The rise of the cross section partly compensates the expected fall of the incident rate. The study of such neutrinos is attracting much attention and ambitious projects are being developed [1,8,9], or considered.

One important problem with point sources such as Cygnus X-3 is their apparently erratic character. Fluxes are such that observations with present detectors have to be considered over several years and different data have to be combined [9,11]. This weakens the strength of the

conclusions which can be drawn, hence the caveat when quoting a neutrino rate over one year. Nevertheless, in order to illustrate the tantalizing features of this physics, it is worth presenting an apparent puzzle and a possible interpretation [11]. The only known, stable and uncharged, primaries which can be associated with a point source are photons and neutrinos. Let us consider such particles at the 1 to 10^4 TeV level. Photons interact violently in the atmosphere. Neutrinos hardly do so. They just pass through. The registered events should correspond to photons.

These photons should have been partly absorbed on the cosmic radiation microwave background. The threshold for electron-positron production in such photon-photon collisions leads us to the 1000 TeV range. Since the distance to the source is known, one can calculate the effect of this absorption on the integral spectrum and, assuming the production spectrum to be smooth in the first place, one expects a relative depletion in the 10^3 TeV range. As shown in figure 2 [11], nothing like that is seen. The data cannot be considered to be fully conclusive. Yet, one is inclined to assume that an unabsorbed component is also at work. If it is due to neutrinos, one would have to conclude that the neutrino cross section is about six orders of magnitude bigger than it should be in the standard model! The neutrino energy threshold corresponding to such a new effect can be estimated from the needed increase at 10^3 TeV. It is then of the order of 1 TeV in the centre-of-mass. This would be new physics, as expected, however, in composite models of quarks and leptons where neutrinos would have strong interaction cross sections at a sufficiently high energy, thus probing their target at very short distance. This is an exciting challenge ! The cross section would have to be of the order of a mb to compensate for the unseen, and expected, depletion [11]. This cross section is much larger than the one expected from a peculiar infrared behaviour in electroweak theory [12], which we already referred to. The neutrinos could however still easily penetrate the atmosphere. Yet some will interact and a welcome consequence is that this would also explain an other puzzling fact, which is that the extensive air showers from point sources seem to contain too many muons for their assumed photon origin. This observation is, however, still under dispute [1]. One is still at the level of hypotheses! Yet this illustrates very well the tantalizing need for more data on the very high energy neutral particles received from such point sources.

It is clear from this overview of cosmic ray physics that there is a strong demand for far more extensive data than those which we have today. The field is actually just opening up to new vistas as very ambitious

detectors are developed. Much can be done on earth. Would experimentation on the moon eliminate shortcomings of experimentation on earth and on satellites ?

3-Moon versus earth operations.

The moon has no atmosphere. It has a very low intrinsic magnetic field and it is well outside the radiation belts. As such, it is a very good observation place for the low energy component of the cosmic ray spectrum (GeV range). Of particular interest is its composition, measuring its antiparticle and heavy element content. This is, however, an energy domain where the global incident flux is large and much could be done with dedicated satellite research, which represent a saving in cost by typically an order of magnitude at equal weight as compared to installation on the moon. Such type of relatively light equipment could however be installed on the moon benefiting from a "lift". With no extra launch involved, the moon would offer an advantageous location. Whilst there are important open questions in this energy range, the special interest of the moon definitely lies in the high energy part of the spectrum where fluxes are very low. One then needs large and steady areas for which the moon would be an ideal platform. One also needs detectors with calorimetric properties which require a large amount of material. This material could to a large extent be found on the moon itself, since a good fraction of the mass is associated with absorbers in the detector. This is an important advantage over satellite studies, which could even extend down to the GeV region for photons. Photons of energy up to 100 GeV are indeed too soft to penetrate the atmosphere and may be too hard for "cheap" satellite studies. The moon could well become the place where to study them. As previously said, one should watch for possible dim lines in the gamma ray spectrum in the multi-GeV range and large arrays offer a definite advantage.

Back to the high energy part of the spectrum, the atmosphere acts as a very valuable converter for photons and more generally as a calorimeter. One would have to replace it on the moon by specially built devices. They would be instrumented calorimeters where the stopping material would be made from moon rocks or dust. The main advantage is that individual very high energy particles could be studied instead of the cascade outcomes which one has to be content with on the earth. One could thus study directly the primary spectrum, measure its composition, and also analyse the dominant features of scattering events at extreme energies, that is much beyond the reach of even the next generation of colliders [4]. To set

the scale, a device of 10.000 m^2 in area would be able to reach up to 10^8 GeV, that is well beyond the first kink in the spectrum of figure 1. This corresponds to 100 events per year. All this would provide very valuable information.

Considering point sources, direct access to the incident photons would be a great advantage in view of the puzzles already mentioned. However rates are then very low ($10^{-11} \text{ cm}^{-2}\text{s}^{-1}$, at 1 TeV) and extensive detectors are needed to compensate for that. To set the scale, one would need a 100 m^2 area to reach beyond 1 TeV at the level of one event per day. This is good but one should still reach 3 orders of magnitude down in rate in order to access the region where the effect of scattering off the cosmic radiation background is particularly marked, as shown in figure 2! Yet, one could see directly what is arriving.

It is clear however that rate is the first problem. The direct determination of the primary comes only next. For that reason, the advantages of the earth, with its being here with the "built in" converter-calorimeter provided by the atmosphere, are hard to beat when it comes to the choice of where to invest the available funding. Yet, it is clear that the moon will be eventually used as a base for such studies.

At a moon base, one could also use the whole atmospheric rim of the earth as a detector to study, from the moon, the Cerenkov light produced by giant air showers. This could be used to extend the detection of the cosmic ray spectrum beyond 10^{12} GeV. Such energies correspond to only one event per 10.000 Km^2 per year!

The rate question is even more important when considering neutrinos. We first consider very high energy neutrinos. The earth atmosphere is a problem when considering the neutrino background associated with the weak decay of high energy secondary particles. For the high-energy part of the spectrum, it is, however, not a serious one. Conditions can be assessed from the measured muon flux, which extends up to 50 TeV. The calculated neutrino spectrum falls steeper with energy than the overall primary spectrum. This results from the fact that pions in particular stand a greater chance of being absorbed before they decay, as their energy increases. For that reason also, atmospheric muons and atmospheric neutrinos have an angular distribution which has a maximum at the zenith, when cosmic neutrinos do not. Atmospheric absorption beats the parent-daughter relationship which, for power law falling spectra, gives the same drop with energy for primary and secondary particles. When considering muons associated with neutrino reactions in a detector, this atmospheric background ceases to be a problem beyond 100 GeV [1]. One

may conclude that, for neutrinos of the order of one TeV or more, it is the size of the detector which matters. A location on the earth is fine and much progress has still to be made with a good case to attract available funding for that research.

The present trend on earth is to use giant water detectors, where the medium provides both stopping power and Cerenkov light. An other considered possibility is to use acoustic detectors spread over a quiet ice cap. This is a technique which could be eventually used on the moon, with acoustic detectors in moon rock, taking then benefit from the relative quietness of the moon.

Having a large neutrino detector on the moon, it would be tempting to use it to detect high energy neutrinos produced by the dump of an accelerator beam on earth. With beams in the 10 TeV range, corresponding to the coming generation of proton colliders, one will produce intense beams of high energy collimated neutrinos. Detecting them also on the moon would provide a great opportunity for neutrino oscillation studies. To set the scale, if one could aim such a 10 TeV beam, after absorption, at a 1 Km^2 detector on the moon, one could get 10.000 events per year [14]. Practical steering of an accelerator beam, which has to be by construction tangential to the earth, is, however, limited to moon rises and moon sets, and the corresponding duty cycle reduces the counting rate by a good factor 1000.

Considering now rather low energy neutrinos, of the order of 10 MeV say, the atmospheric (higher energy) and nuclear reactor (lower energy) backgrounds, proper to the earth, are not a serious problem for solar neutrinos but should be one for the search for neutrino relics of supernova explosions [14]. The importance of the required lunar detectors pushes them to the distant future.

Left are neutrinos in an intermediate energy range, of the order of 1 GeV, for which the atmospheric background is a serious question. It arises from the combined fall of the primary spectrum with energy and the rise with energy of the reaction cross section. In that case, however, the most interesting problem seems to be the background in proton decay. This is a special issue to which we turn.

4-Proton decay on the moon.

Proton decay bears on a fundamental issue. It is a consequence of grand unification schemes which combine quarks and leptons. The relevant energy scale is of the order of 10^{15} GeV. The expected lifetime is

accordingly very long. Present results set a lower limit of $2 \cdot 10^{32}$ yrs for the most easily visible $e^+\pi^0$ mode. Whilst other decay modes could be dominant, one may say that nothing has been seen, all reported events being at least ambiguous. The present limit only rules out the most simple scenario, based on the SU(5) Grand Unified Theory. One should try to reach as far as possible. It is tantalizing to become sensitive to longer lifetimes since supersymmetric versions of Grand Unified Theories give a particularly great importance to values up to 10^{34} or 10^{35} . In reaching that a gain by at least a factor 100 in sensitivity is required, when the background due to muon and atmospheric neutrinos is already a problem [9,10]. Pati, Salam and Sreekantan have long emphasized the particular advantages which a detector on the moon would then offer [10,15]. To set the scale one can consider a lifetime of 10^{33} years. A detector of 10 Kilotons of active material could then yield 6 events per year. One would have to use a relatively fine grained calorimeter but only a few per cent of its total weight would have to be brought from the earth. Most of the detector absorbing material could be assembled from moon dust. The incident flux on the surface of the moon corresponds to a serious background (the flux of 10 GeV protons is as high as $1/\text{cm}^2\text{s}$!). The detector would then have to be seriously shielded. However, an advantageous location could then be a tunnel excavated on the side of a crater, since a thickness of the order of a few 100 of meters of moon rocks should provide enough shielding. This should deal with the hadronic background.

Whilst the neutrino background is reduced by the absence of atmosphere, it is not fully negligible. Short-lived particles with weak decay originating from primary protons interacting with the moon rocks have some time to decay despite the density of the moon dust, which is of the order of 2g/cm^3 . The moon dust surface acts as the atmosphere, producing neutrinos! One can, however, estimate that this background, at the crucial GeV level, would be reduced by a factor 200 as compared to the one which one has to face on earth [10]. Direct cosmic neutrinos are not expected to provide a larger background. One could then gain the factor needed to definitely reach 10^{33} and, may be go up to 10^{34} , thus covering a particularly interesting range.

It may well be that an increase in sophistication of the earth based proton decay detectors, which one may witness before even a cruder detector can be assembled on the moon, will be such that this window in lifetime would have already lost its relevance. This could be the case with detectors becoming sensitive to a whole array of decay channels and

allowing measurements not equally sensitive to the neutrino background. Yet, the possibility of installing such a detector on the moon may still look promising two to three decades from now, if the proton decay lifetime is still out of reach.

5-A very large accelerator on the moon ?

We are always thriving for higher energies and this is bound to continue [16]. Granting a particular technology, reaching higher energies implies an increase in the size of the machines. This is a consequence of synchrotron radiation power for electron accelerators, and of magnet performances for proton machines. The present LEP(LHC) tunnel has a circumference of 27 Km. The circumference of the SSC is three times as large. Accelerator operations call for a good vacuum. For such "real estate" and vacuum reasons, the moon has been sometime mentioned as offering an advantageous location for the accelerators of the distant future. In this prospective survey of high energy physics on the moon, one should then also consider the continuation of accelerator high energy physics on the moon! However, obvious cost consideration notwithstanding, such a future extension does not seem realistic.

Real estate and geology are indeed not the present limitations, once cost constraints have been overcome. At present, tunnelling is no more expensive than cut and fill. Giant machines do not require a very large flat, hard and stable surface area. They can be installed typically hundred or more metres underground, even under populated regions. The present taxing limit on future machines is synchrotron radiation power, which increases as E^4/R , where E is the beam energy and R is the machine radius. LEP is probably the largest circular electron machine ever to be built (100 GeV beams). With protons, the same limitation should be felt not much above the SSC energy (20 TeV beams). Indeed, synchrotron radiation at the SSC represents already a good fraction of the power which has to be removed from the cryogenic system. Great difficulties would have to be overcome increasing the energy, and size, by a factor two. The high energy machines of the future will be colliders. For power limitation reasons, they will use superconducting magnets and/or superconducting accelerating cavities, as those of the present generation already do. Vacuum then comes relatively cheaply with low temperatures and large scale cryogeny should not raise major problems. One may try to overcome the synchrotron radiation limit with linear colliders. Here the problem is luminosity, which has to be obtained without the high frequency multiple bunch crossings of a circular

machine. For physics reasons the luminosity has indeed to increase as the square of the centre-of-mass energy. A fully satisfactory technology for high luminosity linear electron colliders in the TeV range is not yet at hand.

It therefore appears that our progress towards much higher energies is not size limited but technology limited. New ideas and much R&D work are needed to develop ways to obtain large energy increases per metre for intense beams, and to focus them properly. This is earth-based development and construction work for the foreseeable future.

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Figure captions.

Figure 1 [1]. The integral cosmic ray flux. To a good approximation, one can say that the rate above $E(\text{GeV})$ is $(E/10^{10})^{-2} \text{ Km}^{-2} \text{ year}^{-1}$.

Figure 2 [11]. Integral spectrum from Cygnus X-3 with calculated spectrum associated with fits to the data. The dashed line corresponds to incident photons only. The solid line involves an extra component.

References.

- [1] P.Grieder. CERN Summer School (89), and references therein. This paper contains much information about very high energy cosmic rays and covers in particular the question of cosmic neutrinos.
- [2] M.Samorski and W.Stamm. Ap.J.Lett. 268 L17(83).
- [3] C.Fichtel and J.Linsley. NASA 85-003 (85).
- [4] At present, the successful operation of the CERN p-pbar collider is coming to an end. Over the past decade, it provided a centre-of-mass collision energy of 630 GeV. Now, the Fermilab collider gives 1.8 TeV p-pbar collisions.

The Superconducting Supercollider (SSC) will give 40 TeV p-p collisions and the CERN-LHC will give 16 TeV p-p collisions. The energy of the coming generation of colliders corresponds to the 10^8 to 10^9 range for incident cosmic ray protons.

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Fig. 1

Fig. 2