PROSPECTS FOR PARTICLE PHYSICS AND ASTROPHYSICS WITH COSMIC RAYS*

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Summary

The field of high energy cosmic rays forms a bridge between high energy physics and astrophysics. In this paper we review the present status of the field and plans for new experiments, especially those in the U.S. We expect significant further progress from the study of small air showers in the 10^{15}-10^{16} eV range when such indirect experiments have been calibrated by direct measurement of the primary cosmic ray composition to $\sim 10^{14}$ eV and by collider experiments around $\sqrt{s} \sim 1$ TeV. At higher energies we expect progress to focus on the Fly's Eye experiment at Utah and possible new related experiments. Such experiments explore energies up to $\sim 10^{20}$ eV or $\sqrt{s} > 100$ TeV. Searches for cosmic ray antimatter, studies of nucleus-nucleus collisions around 100 GeV/nucleon and studies of cosmic ray neutrinos may also yield results of great interest for high energy physics and astrophysics.

1. Introduction

From the point of view of high energy physics there are several reasons to study cosmic rays: 1) to explore particle interactions at energies much higher than those accessible at accelerators, 2) to study processes involving neutrinos and high energy nuclei that are also inaccessible to present machines and 3) to look for signals from the early Universe, such as a cutoff of cosmic rays above 10^{20} eV due to the 3^{o} blackbody radiation, or the presence of antinuclei, which bears on the question of whether or not the universe is baryon symmetric on the largest scales. In addition there is considerable scope for applying particle physics to the study of cosmic ray astrophysics, i.e. to determine the chemical composition and energy spectra of the primary cosmic rays, which in turn reflects their origin, acceleration and propagation. Indeed, cosmic ray physics has been and will continue to be a bridge between particle physics and astrophysics.[1]

It is natural to divide the high energy regime into three parts: roughly, 10^{12}-10^{14} eV, 10^{14}-10^{16} eV and $>10^{16}$ eV. Different types of experiments are suited to the different regions as determined by the flux. This is indicated in Fig. 1, which shows the integral flux as a function of primary energy[2] with some names of experiments superimposed at their characteristic energies. A scale showing equivalent nucleon-nucleon center of mass energies is superimposed. Note that the region of the second generation hadron colliders to a large extent overlaps the 10^{14}-10^{16} eV region, which includes an astrophysically interesting steepening of the overall energy spectrum. After a brief description of the status of searches for antinuclei in the cosmic rays, we will discuss each of the high energy regions in turn. There is an Appendix that lists existing and proposed U.S. experiments. The use of cosmic rays to search for neutrino oscillations with deep detectors is discussed elsewhere in this volume.[3]

In looking to the future, we want to look for opportunities to make substantial, qualitative advances over previous work in the field; to be able to reach definitive conclusions where perhaps only hints existed previously. For reasons to be outlined

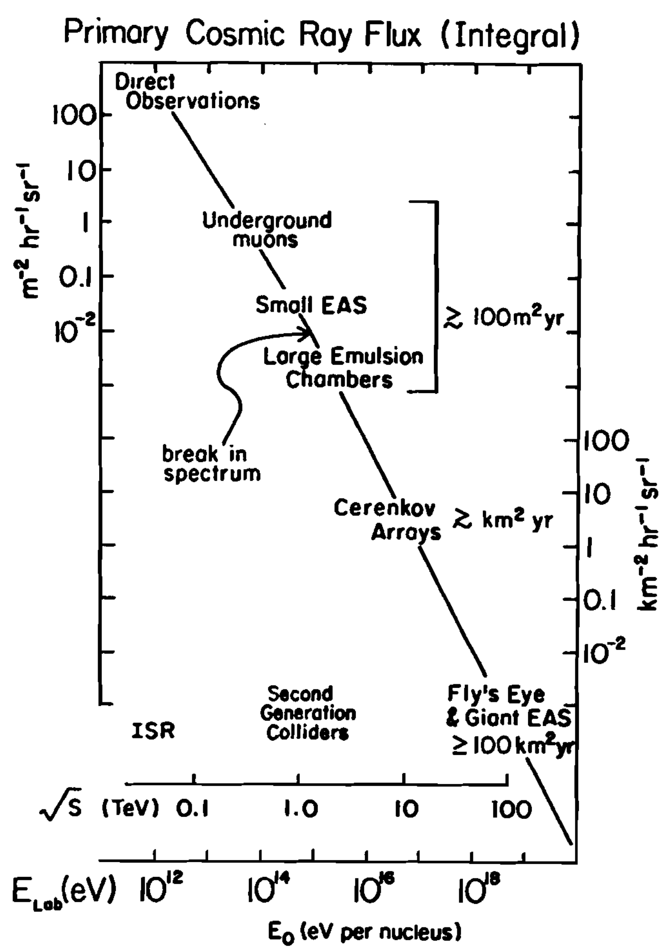

Fig. 1

* Summary of the cosmic ray subgroup at the DPF summer study, Snowmass, 1982.
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below we believe there are now several such opportunities.[4] These include a significantly improved search for antinuclei; detailed studies of energetic nucleus-nucleus collisions at ~1 TeV/nucleon; direct determination of the primary composition in detail to ~10^{14} eV; determination of the relative fractions of four or five major groups of primary nuclei around 10^{15} eV where the energy spectrum begins to change; evaluation of the ratio of processed (C,O, Fe) to primordial (p, α) nuclei around 10^{18} eV where the cosmic rays may be extragalactic; and a measurement of the proton cross section around $\sqrt{s}$ ~ 50 TeV.

2. Antimatter Searches

The Universe appears to contain mostly baryons rather than antibaryons out to the scale of the local supercluster of galaxies.[5] Though baryon asymmetry of the entire Universe may have a natural explanation within grand unified theories[6] there is little or no experimental evidence on the baryon asymmetry question on larger scales. While recent observations[7] report fluxes of cosmic ray antiprotons significantly higher than expected within conventional models of cosmic ray propagation, it is still quite possible that they are secondaries of collisions between ordinary cosmic rays and interstellar matter.[8] A current experiment[9] to confirm the earlier result will, if it is positive, probably lead to the conclusion that cosmic ray protons traverse more matter than had previously been thought rather than to the conclusion[10] that the Universe is baryon symmetric, though this is to some extent a matter of taste.

On the other hand, cosmic rays with $Z<-1$ would be most unlikely to originate as secondaries in collisions of ordinary matter, so their observation would force the conclusion that there are distant large-scale regions of antimatter accelerating anti-cosmic rays. Elsewhere in this volume, Price[11] describes a proposed experiment capable of pushing the search for anti-iron to the level of $\overline{Fe}/Fe \sim 10^{-7}$. As he argues, this should be sufficient to see extragalactic anti-cosmic rays if they exist.

3. Direct Observation of Primaries

Because of the steeply falling primary spectrum there is a natural dividing line around 10^{15} eV (or somewhat lower) between direct and indirect experiments. The total flux above this energy is only about 2 particles per m^2 per week per sr at the top of the atmosphere. Direct measurements with resolution <1 charge unit now extend to just above 10^{12} eV/nucleus.[12] The current JACEE series of balloon flights[13] has detcted some tens of primary cosmic rays with energies between 10^{14}-10^{15} eV, and this number will be increased. The University of Chicago experiment[14] to be flown in the Space Shuttle in late 1984 will extend high resolution, high statistics determination of the primary composition for $3<Z<56$ to well above 10^{13} eV. A one year exposure on a space platform, as proposed by the Goddard, Maryland, Chicago collaboration[15], would extend such measurements for all $Z \lesssim 56$ to almost 10^{15} eV/nucleus.

Since the flux decreases by about two orders of magnitude per decade increase in energy, it would appear impractical to go any higher in energy with direct observations above the atmosphere. In particular, it is unrealistic to hope to do pp physics significantly above collider energies with space experiments. Above 10^{16} eV, the primary flux is only 1 m^{-2} sr^{-1} yr^{-1}; a realistic 10 ton payload for the Space Shuttle, for example, containing a 3λ calorimeter, a target, and appropriate counters and chambers would have an admittance of only about one m^2 sr and hence a rate of one event per year above 10^{16} eV.

On the other hand the 10^{12}-10^{14} eV/nucleus range is quite novel for studies of nucleus-nucleus collisions. The JACEE collaboration[13] has as one of its primary aims investigations of collisions between nuclei at high energy, and several interesting events from that experiment have been described in some detail. There is a proposal for study of collisions between heavy nuclei from the University of Minnesota group[16] for the Space Shuttle. A physics motivation here is to search for possible new states of collapsed nuclear matter which may occur when heavy nuclei collide at high energy.[17]

4. The 10^{14}-10^{16} eV Range

Until ~one year space platform experiments occur, the upper limit for direct observation will be < 10^{14} eV. One year exposures in space can extend this to $\lesssim 10^{15}$ eV. To probe higher in energy requires use of large areas exposed for long times deep in the atmosphere. There are several experiments of this kind:

1) Observation of muon groups in underground detectors. This is an old subject which can be significantly extended by proton decay experiments because of their large area and/or high resolution.[18] The basic idea is that the rates of multiples are sensitive to primary composition because a heavy nucleus is more likely to produce a multiple muon event than a proton primary - provided the energy per nucleon is sufficiently above threshold for production of muons in the atmosphere that can survive the depth of the detector[19]. There is also sensitivity to prompt muon production through angular dependence as well as relative rates of multiples. The power of these experiments can be extended by measuring the muon separation distribution with an outrigger detector and by using a surface array in coincidence with the underground detector. These are both being considered by the proton decay experiments, and the Homestake group has begun to construct a surface array. The separation distribution is necessary to interpret measurements with detectors that are smaller than or comparable to the lateral spread of individual showers. The surface array can roughly classify the event as to primary energy by measuring the accompanying electromagnetic cascade.

2) Studies of small air showers. An example is the series of experiments by the Maryland group[20] measuring delays of energetic hadrons behind the air shower front. Observation of a large fraction of events with such delayed hadrons led to the conclusion that the fraction of heavy nuclei in the primary beam is increasing in the range of 10^{13}-10^{15} eV.

3) Observation of air shower cores, e.g. in emulsion chambers. Large emulsion chambers (~50 m^2) have not so far been used by U.S. groups. There are three main experiments of this type[21]: a Brazil-Japan collaboration experiment at Mt. Chacaltaya in Bolivia; a Soviet-Polish collaboration in the Pamir Mountains and a Japanese experiment at Mt. Fuji. Very energetic (> 2 TeV) subcores of air showers are measured. Subcore multiplicities and lateral distributions reflect composition as for multiple muons. Overall fluxes are also quite sensitive both to composition and to the hadron interaction cross section. Both a large fraction of heavy nuclei around 10^{15} eV and a large cross section (σ_{pp}^{Tot} ~60-70 mb around $\sqrt{s}$ ~ 1 TeV) are suggested by the data.[22] The interpretation of

these data in terms of composition and of the properties of elementary interactions depends on careful Monte Carlo calculations of the propagation of the primary through the atmosphere to the detector. For example, the interpretation of the famous Centauro I event of the Brazil-Japan group at Chacaltaya as a primary proton which penetrated 500 g/cm^2 of air and then produced a single interaction 500 m above the detector, resulting in the observed 50 hadrons, may be a very simplistic picture. The "C-jets", wherein an interaction occurs in a hydrocarbon layer 1.5m above the emulsion chamber, are much cleaner in their interpretation, but most emulsion chamber groups seem to be focusing on the "A-jets" as they sample somewhat higher energies.

More recently, three groups plan to combine electronic detectors with emulsion chambers. Matano et al. at Chacaltaya[23] have operated a scintillation counter layer under a modest emulsion chamber together with an air shower array, and the Mt. Fuji group propose to use an air shower array in conjunction with their large emulsion chamber.[24] A very ambitious project is underway in Armenia by a joint Soviet group at Mr. Aragatz. The experimental hadron research installation (ANI) will consist of a 1600 m^2 emulsion chamber interleaved with an ionization chamber calorimeter. All of this overlies an underground muon facility and is at the center of an air shower array.[25] This project will take several years to complete, and is aimed at understanding hadron interactions over the energy range 10^{15}-10^{18} eV.

One way of using such instrumented calorimeters is to look for events initiated by surviving primary protons, by identifying interactions not accompanied by a coincident air shower. This would indeed identify a sample of data which could be interpreted cleanly, but at a considerable sacrifice in rate. The fraction of such primaries that would survive to Mt. Aragatz, for example is ~10^{-3}, so that a 1000 m^2 array would only observe about one event per year of this type above 10^{16}eV. It may also be possible to study air shower subcores with large fine-grained muon-hadron calorimeters. With this in mind, the Maryland group recently triggered the Fermilab neutrino detector E594 on air showers to look simultaneously at subcores and energetic muons in shower cores.[26] This is an interesting possibility because, for example, a change of inelasticity and multiplicity that might be associated with production of collapsed nuclear matter could diminish the number of energetic hadrons per shower while simultaneously increasing the number of muons.

All of these indirect, cascade experiments in the 10^{14}-10^{16} eV range require extensive calculation for their interpretation. The fact that hadron interactions in this energy range ($\sqrt{s}$ ~ 0.4-4.0 TeV) are being explored directly at new colliders will make the calculations much more reliable than previously. In fact, early SPS pp collider results have already played a role in establishing the conclusions about heavy primaries and increasing cross section referred to above by ruling out the possibility that the observed effects are due to a very rapid increase in multiplicity in hadron-hadron collisions (i.e. $\langle n \rangle \propto s^p$ with $p \gtrsim 1/4$).

Detailed direct measurements of the composition to ~10^{14} eV, by calibrating cascade measurements at low energies, will also greatly enhance the power of the indirect measurements to determine relative fractions of the main nuclear groups (p, α , C+O, Mg+Si and Fe) in the 10^{15}-10^{16} eV range where the change in the spectrum occurs. It should be possible to determine whether the feature that shows up at 10^{15}-10^{16} eV total energy is due to a break in the magnetic rigidity spectrum occuring in the 10^{14}-10^{15} V range. (If so the proton spectrum would bend at 10^{14}-10^{15} eV but the effect on the overall spectrum could be delayed to higher energy where heavier nuclei reach the rigidity limit. Some of these points are illustrated in Fig. 2.) In any case, the indirect experiments should play an important role in unravelling the astrophysics of this crucial energy range.[27] Because of the coincidence of new collider experiments and new direct measurements of composition to ~ 10^{14} eV, which will support indirect experiments to 10^{16} eV, the prospects for major new progress here are great.

5. The Highest Cosmic Ray Energies

At energies well beyond 10^{16} eV the goal is to study both log(s) physics and primary composition and energy spectra. Air shower detectors of very great collecting power are necessary to overcome the exceedingly low flux. The major U.S. effort in this area is the Fly's Eye experiment[28] of the University of Utah group that detects atmospheric fluorescence. It has an effective area > 100 km^2 (depending on energy) and can see full profiles of individual showers as they develop in the atmosphere. This is in contrast to classic air shower experiments that sample the cascade at only one depth - ground level. The present detector is sensitive to showers with $E_0 >$ 3x10^{17} eV ($\sqrt{s}$ > 25 TeV) up to E_0 ~ 10^{19} eV. A future goal is to

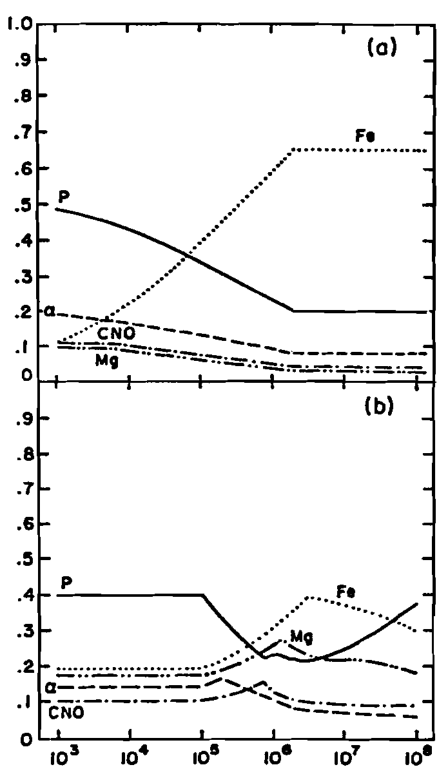

Fig. 2. Two possibilities for an increasingly heavy composition suggested by the U. of Maryland delayed hadron experiment.[20] The two are essentially the same at 10^4 GeV. In (a) only Fe is increasing. In (b) all heavies increase relative to protons because all spectra steepen at a rigidity of 10^5 GV. Also (b) assumes an extragalactic proton component coming in above 10^7 GeV.

extend measurement of the primary energy spectrum to 10^{21} eV to settle the question of whether there is a cutoff due to photopion production on the 3° background radiation.

Calculations[29] show that the observable distribution of depths of maximum is sensitive to the proton-air cross section, and preliminary measurements suggest[28] $\sigma_{air}^{inel} \simeq 500$ mb around $\sqrt{s} \sim 20$ TeV, about 70% higher than its low energy value. The result is extremely preliminary and depends among other things on the assumption that the primaries above 3×10^{17} eV contain a significant fraction of protons. Other experiments (summarized in Fig. 3) indeed suggest a transition to light primaries at high energy, perhaps associated with a transition to extragalactic cosmic rays.[30] Many of these measurements of mean depth of maximum were made with experiments that detect atmospheric Cerenkov light, a technique that bridges the gap between 10^{15} eV and Fly's Eye energies ($>3 \times 10^{17}$ eV). (Experimental references are given in Ref. 31, from which Fig. 3 is taken.)

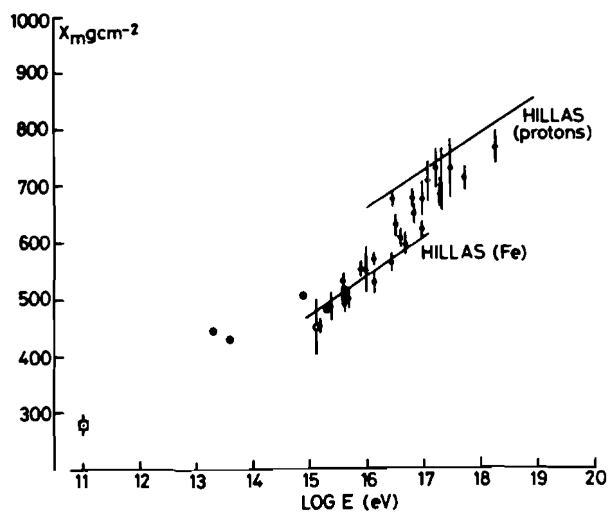

Fig. 3. Summary of data by Watson (Ref. 31) which may be interpreted to suggest a transition from predominantly heavy primaries around 10^{15}-10^{16} eV to mostly light primaries (p and α?) around 10^{17}-10^{18} eV. The graph shows slant depth of shower maximum (measured from the top of the atmosphere in gm/cm^2) as a function of primary energy per nucleus.

The questions in particle physics which could be studied at these energies, besides total cross sections, include average multiplicity, transverse momentum distribution, a search for evidence for significant prompt muon production, and possibly rapidity distributions. Meager though this may be, it is possibly our only access to energies above 10^{17} eV before the end of this century!

Planned refinements of the Fly's Eye detector include filters to reduce contamination from Cerenkov light and a second eye (8 mirrors of which already exist) to give a stereo view. Both will lead to improved resolution for the early portion of shower development which is necessary for a measurement of the primary composition. Even a measure of the ratio of light primaries (p and α) to all heavier nuclei would be of great astrophysical interest because it is essentially the ratio of primordial nuclei to material processed in stars.

Other possibilities under consideration with the Fly's Eye include a higher resolution eye (10,000 phototubes instead of 1000) and a surface muon/electron array which would be calibrated by Fly's Eye and used to extend the duty cycle of the experiment by more than an order of magnitude. It would also give independent information on cross section and multiplicity in hadron collisions and on primary composition. These and other current, proposed and possible cosmic ray experiments are summarized in the Appendix.[32]

6. Conclusion

Beyond the activities already in progress and discussed above, we identify the following significant opportunities for advances in our knowledge of particle physics and astrophysics well above this decade's $\bar{p}p$ collider energies.

An elaboration of the Utah Fly's Eye detector with a surface air shower array would improve the clarity of interpretation of a fraction of the Fly's Eye events, would extend the live time by an order of magnitude, and would also permit the correlation of these data with the extensive existing library of air shower data. It might be possible to develop lightly-shielded muon counters using transition radiation detectors that could separate low energy muons (~1 GeV) from higher energy muons ($\gtrsim$ 100 GeV); adding these to the array might more effectively accomplish the objectives discussed above in connection with underground muon detectors. Electronic hadron calorimeters could also be considered, although any practical area (~$10^3 m^2$) restricts the energy range to which they would be sensitive to < 10^{17}eV.

It is our belief that the approach outlined above of elaborating around the Fly's Eye (as a central facility) is a more promising avenue than the large instrumented emulsion chamber described by the Russians[25], for both particle physics and astrophysics.

We also believe that an international program employing this broad spectrum of detectors (fly's eyes, large-area surface array, sophisticated muon detectors, and perhaps hadron calorimeters and Cerenkov detectors) should be developed at a very high altitude site such as Chacaltaya (5200 m) where air showers are "younger", interpretation of the physics of the first interaction is cleaner, and the observing conditions for the fly's eye could be better.[33]

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Appendix

U.S. Cosmic Ray/Particle Physics Program

1. Antimatter search
   a) Golden et al. $\bar{p}$ ~1-2 GeV, (1982)
   b) Price et al. $\overline{Fe}/Fe$ to 10^{-7}, (proposed > 1984)
2. 10^{12}-10^{14} eV: Direct observation of primaries
   a) JACEE, W.V. Jones, U.S. Spokesman - composition and nucleus-nucleus interactions to 10^{14} eV (currently in progress)
   b) Chicago Space Shuttle experiment
      $Z>3$ composition to $>10^{13}$ eV/Nucleon (1984-85)
   c) Goddard-Maryland-Chicago
      Space Shuttle-Space Platform, all Z to > 10^{14} eV (proposed ~1990)
   d) U. of Minnesota
      Nucleus-Nucleus in Space Shuttle (proposed ~1990)
3. 10^{14}-10^{16} eV, $\sqrt{s}$~0.4-4 TeV
   a) U. of Maryland, Delayed Hadrons in EAS (currently in progress)
   b) All proton decay groups, multiple muons underground (currently in progress)
   c) Homestake group
      Surface array over underground detector (construction begun.)

Outrigger and surface arrays are being considered by all p-decay groups

   d) Search for $Z>10$ penetrating particles over EC at Chacaltaya - possble connections with Centauro. P.B. Price et al. 15 m^2 yr of CR-39 exposed so far, could go to 150 m^2 in a year with existing structure.

No current U.S. Activity in large emulsion chamber (EC). Japanese groups and Soviet group are separately planning EAS/large EC combination

   e) Possible future development
      Multi-faceted High altitude Cosmic Ray Studies:
         EAS+EC+muons and hadrons
      Fine-grained hadron-muon calorimeter to study EAS cores.
         There is a current U. of Maryland Test triggering FNAL E594 neutrino detector on Cosmic rays.
      Large area near-surface (shielded) muon array (e.g. with TR detectors) to do multiple > 1 TeV muons without going deep underground.
4. $>10^{17}$ eV, $\sqrt{s}$ ~ 20-100 TeV
   a) U. of Utah Fly's Eye
      Goal: composition and log(s) physics to $\sqrt{s}$ ~ 100 TeV (currently in progress).
      Current plans include:
         Adding filter to reduce scattered Cherenkov light background and developing a 2nd Eye for stereo view.
      An ambitious goal is to
         explore the predicted 10^{20} - 10^{21} eV cutoff
   b) Future possibilities:
         High resolution eye (1000→10000 tubes)
         Surface electron and/or muon arrays with Fly's Eye:
         Improve duty cycle; improve composition/σ resolution
   c) No current U.S. activity in Cerenkov studies of air showers above 10^{16} eV, but this is another possibility. Several U.S. groups are working on Cerenkov studies of smaller showers for gamma ray astronomy: T. Weekes, Mt. Hopkins Observatory, R. Lamb, Iowa and J. Fry, U. Camerini, et al. U. of Wisconsin.