HIGH ENERGY INTERACTIONS OF COSMIC RAY PARTICLES†

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INTRODUCTION

This report focuses on the highlights of seven sessions of the Conference dealing with high energy interactions of cosmic rays. The session titles were HE 1.1: High Energy Cross Section Measurements, HE 1.2: Particle Production-Models and Experiments HE 1.3: Nuclei and Nuclear Matter, HE 1.4: Nucleus-Nucleus Collision, HE 6.1: Searches for Magnetic Monopoles, HE 6.2a: Studies of Nucleon Decay, and HE 6.2b: New Particle Searches. My task is made easier by three other related talks at this meeting; the summary of the current state of elementary particle physics in an invited lecture by Professor Perkins, the rapporteur lecture on emulsion chamber observations by Professor Shibata, and the highlight lecture on nucleus-nucleus interactions by Dr. Wosiek.

Let me begin by recalling the familiar integral flux of cosmic rays versus energy in Figure 1, where noted on the graph are the energies available and to become available with various of the proton-proton or proton-antiproton colliders. It is against this backdrop of available accelerator energies at high energy laboratories that we must temper our studies of particle interactions from cosmic rays. Let me recall Perkins' lecture and repeat his summary perspectives on the outstanding classes of problems in particle physics and the extent to which cosmic ray experiments might be useful in shedding light on these problems.

Outstanding Problems in Particle Physics and the Relevance of Cosmic Ray Data to their Solutions.*

PROBLEMS	COSMIC RAY RELEVANCE
• Massive Scalar Particles (Higgs Sector)	No
• Technicolor, Supersymmetry (New Particles, TeV Masses)	No
• Tests of GUTs (Magnetic Monopoles, Proton decay, etc)	Yes
• Neutrino Mass, Mixing; Majorana Neutrinos	Yes
• CP Violation	No
• New Interactions (Centauros, etc.)	?
• Unexpected Phenomena	Yes, if done well

*taken from D. Perkins lecture at this meeting.

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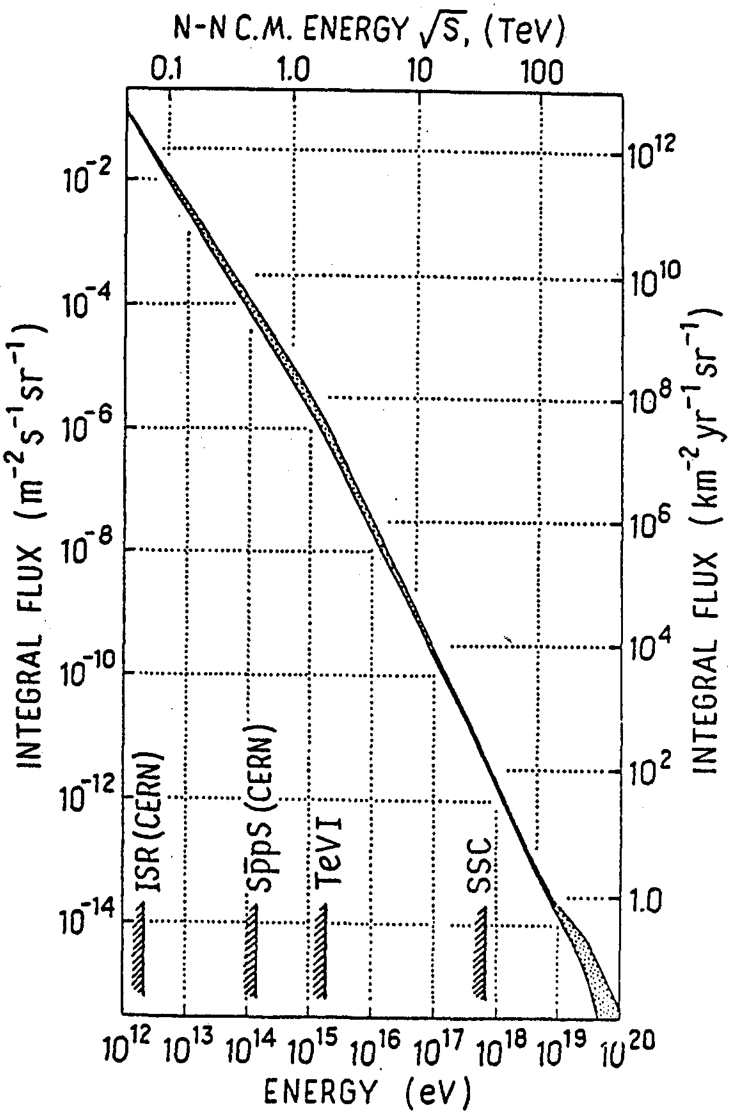

Figure 1. Cosmic ray primary integral flux spectrum vs. energy, with energies of nucleon-nucleon colliders indicated on the abscissa.

Note that the dominant problems in particle physics, the search for the Higgs particles and the search for evidence of Supersymmetry, Technicolor, or other departures from our current standard model are apparently not accessible to study by cosmic ray interactions. Looking down this list, it appears that our cosmic ray efforts have been primarily directed toward the last two items; the search for evidence of new interactions, such as Centauro events, Chirons, etc., and the search for unexpected phenomena.

I believe that Perkins' summary is a bit narrow in the context of the overall mission of our study of elementary particle physics using cosmic rays. Let me illustrate what I mean with Figure 2. In this simple sketch I attempt to indicate that the four areas: cosmic ray physics, physics of elementary particles, astrophysics, and cosmology are all interrelated. I will not in this discussion elaborate on the relationships between astrophysics and cosmology, astrophysics and particle physics or cosmology and elementary particle physics. I should note however that the relationship between cosmic rays and elementary particle physics is a two-way street. Perkins remarked specifically on the information that cosmic ray physics can provide to help us in understanding elementary particle physics. Equally, or perhaps more important, is the information that we gain from studies of elementary particle physics with accelerators which helps us to interpret cosmic ray data, often at higher energies than available in the laboratory, in order to provide insights and important information which in turn bear on questions in cosmology and astrophysics.

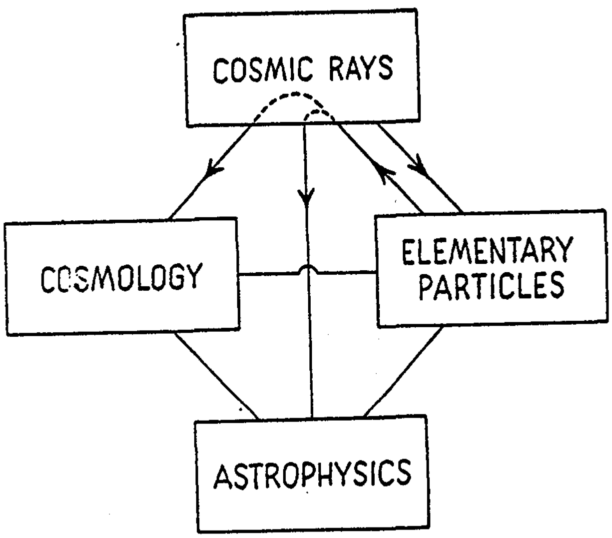

Figure 2.

I would like to propose the following list of areas where cosmic ray studies of high energy interactions are valuable.

(1) Cosmic rays can be use to exlore the fundamental nature of particle interactions at energies greater than those available with colliders, currently about 10^{15} eV. Here cosmic rays may indeed only be able to study gross features of the interactions such as total cross sections, average transverse momenta, average particle multiciplities, and so forth. Nevertheless, even this guidance to the nature of strong interactions well beyond energies accessible with accelerators is valuable.

(2) The study of proton-nucleus interaction properties at energies greater than one TeV, the highest proton beam energy currently available.

(3) The study of nucleus-nucleus reactions at energies greater than those provided by the Berkeley Bevalac or the Dubna heavy ion accelerator, which correspond to about 10^{10}eV per nucleon.

(4)The exploration of the cosmic ray energy spectrum and composition for energies greater than about 10^{14}eV. The indirect data from extensive air showers is interpretable in terms of spectrum and composition only through the use of data from accelerators.

(5) The search for new particles in cosmic rays such as magnetic monopoles, tachyons, quarks, and so forth will continue to be a domain of cosmic rays study. These particles might either be produced in very high energy interactions or, more probably, they may be relics of the early universe and primordial in nature.

CROSS SECTIONS

Let me first address the subject of proton-air cross sections and their interpretation in terms of proton-proton total cross sections. There were several papers presented here which bear on this question. Linsley (HE 1.1-1) reviewed and analyzed a large body of existing data. The Utah Fly's Eye group reported (HE 1.1-2) a relatively clean measurement of interaction mean free path of proton primaries in air and Yodh and his collaborators analyzed the proton-air data in terms of proton-proton cross sections. There were also contributions by Carlson (post-deadline paper) reporting on the UA5 collaboration results from the CERN $\bar{p}$-p collider operated at up to 900 GeV total center-of-mass energy.

The Fly's Eye result on the distribution of the height of shower maximum is reproduced in Figure 3. The data show a rise to a maximum number of events at a depth in atmosphere of about 700 g/cm^2 and then an exponential decay over the range from 800 to 1100 g/cm^2. The Fly's Eye group interprets these data as evidence for the contribution of heavier nuclei interacting at shallower depths in the atmosphere, where maximum occurs closer to the top of the atmosphere, and for proton-air interactions in the exponential tail of the interaction distribution

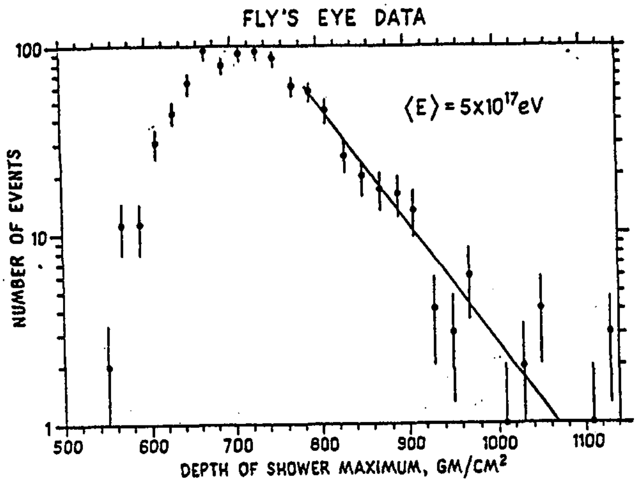

Figure 3. The Fly's Eye data on height of shower maximum showing the exponential component identified as due to proton-air events.

beyond 800 g/cm^2. From these data the Fly's Eye group interprets the interaction mean free path of protons in air as 70 ± 6 g/cm^2 at an average energy of 5x10^{17}eV. Ellsworth, Gaisser, Stanev, and Yodh (Phys. Rev. D 26, 336 (1982) have parameterized the interaction mean free path as determined from this experiment in terms of a proton-air inelastic cross sections and conclude that the proton-air cross section is 540 mb.

The interpretation of this cross section in terms of a fundamental proton-proton total cross section is indirect. The proton-air cross section may be expressed as a sum of the dominant inelastic cross section (which is that observed in the Fly's Eye and most other experiments), plus an elastic scattering contribution, plus a quasi-elastic contribution (wherein the proton scatters off a nucleon in the air nucleus leading to disruption of a nucleus without meson production), and plus a single diffraction contribution (wherein the incident proton excites a nucleon in a nucleus to a nucleon isobar, again leading to soft particle production but not contributing to an air shower). The proton-air inelastic cross section can be related to the proton-proton total cross section through Glauber theory with two added inputs; one an estimate of the quasi-elastic and single diffractive cross sections and two, the proton-proton elastic scattering slope parameter. In fact, Yodh and his collaborators (HE 1.1-3) have embphasized that there may be significant uncertainty in choosing the slope parameter and that different values lead to different values of proton-proton total cross section for the same proton-air inelastic cross section. They have been guided in their choice of the slope parameter from work of Block and Cahn. The collider data best fit a model which leads to a slope parameter of 12 $(GeV/c)^{-2}$ at the energy of the Fly's Eye data. Yodh's analysis of the Fly's Eye proton-air inelastic measurement leads to a proton-proton total cross section at $5x10^{17}$eV of 122 mb.

NEW COLLIDER DATA

Gaisser and Halzen (HE 1.2-2) spoke on the interpretation of the rising proton-proton cross section in terms of quark-quark, quark-gluon and gluon-gluon hard scattering, or jet production. Cline reported on the recent CERN 900 GeV data observed in the UA1 detector which suggested that jet production might account for as much as 20% of the total proton-proton inelastic cross section at that energy (post-deadline paper). The recent data reported by UA1 also indicate that the average tranverse momentum continues to increase in proportion to the particle multiplicity per unit rapidity. There had been an earlier suggestion that the average transverse momemtum plateaued at greater than about 10 particles per unit rapidity suggesting that there was evidence for the onset of quark-gluon plasma phemonena, however the recent data do not support that suggestion.

Data from the CERN Collider reported by Carlson and by Geich-Gimbel of the UA-5 group also included recent measurements of average particle multiciplity, multiciplity distributions and rapidity density. One interesting result was the nature of the multiciplity distributions at these higher energies. They do not follow KNO scaling, which had become a favorite model from ISR data. In fact the suggestion here is that the better fit is to a negative binomial distribution. They also reported their best understanding at this time of the proton anti-proton total and elastic cross sections. Table I is a summary of ISR results and the CERN Collider results on cross sections.

Table I. CERN Collider Results on Nucleon-Nucleon Cross Sections

	ISR (pp)	SPS ($\bar{p}p$)		
$\sqrt{\sigma}$(GeV)	53, 64	200	540	900
σ(total)mb	44	52.3[1]	61.9	66.5
σ(elastic)/σ(total)	0.175	0.187[1]	0.215	0.235[2]
σ(elastic)mb	7.7	9.8	13.3	15.6
σ(inelastic)mb	36	42.5	48.6	50.9
σ(single diff.)[3]mb	7	4.7	{5.2[4] 8.1[5]	7.1
σ(non single diff.)mb	29	37.8	42	43.8
σ(sd)/σ(el)	0.9	0.48	0.5	0.46

1. Interpolated
2. Extrapolated
3. $M^2/s < 0.05$
4. UA5
5. UA4

One interesting feature apparent here is the rise in the ratio of the elastic to the total proton anti-proton cross section with energy.

Rapidity density fluctuatious are seen in the UA5 data which are not associated with jet production and raise interesting questions. Other results from these studies include the observation that no evidence for Centauro events is found. The rapidity distributions almost scale in the rest frame of one of the particles as one goes from the ISR energies through 900 GeV. There are some departures from scaling as suggested by Gaisser and Halzen which can be understood by the depletion of the forward particles through the increased contribution to the cross sections of large-angle jet production. The central rapidity density rises as lns through 900 GeV. At 900 GeV the average charged multiplicity is $\langle n_{ch}\rangle=34.6\pm0.7$, not including single diffraction. Its energy dependence may be fit by either $\langle n_{ch}\rangle= a + b\, s^{\alpha}$ or $\langle n_{ch}\rangle = a + b \ln s + c (\ln s)^2$.

PROTON-NUCLEUS COLLISIONS

One session at this meeting was taken up with reports on nucleon-nucleus interactions. Proton-nucleus interaction systematics are necessary to understand and to calculate the cascading of cosmic ray nucleous in the atmosphere or in thick detectors, such as emulsion stacks. Thus the character of the interactions of primary protons in complex nuclei, such as the distributions in number and momentum of the secondary particles produced in the interactions, and the dependence of the distributions on the mass number of the nuclear target are all essential inputs to the modeling of extensive of air showers or the interactions of cosmic rays in thick detectors such as the nuclear emulsion chambers of high altitude experiments. However, it is less clear that there is a fundamental interest in the understanding of proton-nucleus interactions in terms of elementary particle physics. Given the availability of proton anti-proton collider data over the same range of center-of-mass energies, most of what is observed can be understood as a super-position of proton-proton interactions sumed over the nuclear targets. The uncertainty of the superposition models is greater than the differences between models of primary interactions or the statistical uncertainties in the data. In contrast, nucleus-nucleus interactions hold the promise of observing quark gluon plasma effects and with them the possible phase transition to a new state of matter. Nevertheless, some proton nucleus data are noteworthy. At this conference there were new data presented from the Armenian group (HE 1.1-5) on pion and nucleon cross sections at an average energy at 1300 GeV, as indicated in Table II. The transverse momentum distribution of proton-iron interactions has been observed (HE 1.2-11) to follow an exponential distribution with an average transverse momemtum of gammas of 0.19 GeV/c for gamma rays greater than or equal to 30 GeV/c from events of 2 1/2 to 8 1/2 TeV. Among the most interesting results reported was an observed anomalous fluctuation in rapidity density reported by Capdeville in emulsion events with incident protons and $\sum E_{\gamma}>200$ TeV (HE 5.1-5).

Table II. Data on Inelastic Cross Sections at <E> = 1300 GeV

Projectile particle	Target element	Inelastic Cross Section (mb)
n	C	238 ± 13
p	C	236 ± 13
π	C	181 ± 12
n	Pb	1885 ± 70
p	Pb	1793 ± 90
π	Pb	1646 ± 76

NUCLEUS-NUCLEUS INTERACTIONS

Nucleus-nucleus physics was summarized at this meeting in an excellent highlight lecture by Dr. Wosiek. Several contributed papers were presented from the JACEE collaboration as well as accelerator data from the Dubna and Berkeley heavy ion accelerators. From Dr. Wosiek's highlight talk, I may repeat the essential conclusions. First, at energies below 100 GeV per nucleon the nucleus-nucleus data can be understood as a superposition of nucleon-nucleon physics together with Glauber screening, etc. Model uncertainties are at least as great as the uncertainties in the data, as remarked in the case of proton nucleus interactions. In contrast, at energies greater than 1 TeV per nucleon, the inclusive data as well as multiciplities are consistant with conventional superposition models, but there are characteristics which are not explained by superposition models. The average transverse momentum is anomalously high, there are fluctiations in rapidity density greater than one would expect from statistical arguments and super position models, and there is evidence of an increase of average transverse momentum with an increase in the energy density of the nucleus-nucleus collision system.

MAGNETIC MONOPOLES

At this conference there was a discussion of searches for magnetic monopoles. Three classes of new results were presented. Searches using gas filled proportional counters incorporating helium, where a prediction by Drell and collaborators suggests that the sensitivity to magnetic monopoles extends to lower velocities than is the case of other ionization detectors; scintillation counter detectors and ordinary gas proportional counters; and a report on searches for monopoles in geological samples of mica using track etch techniques. Let me review briefly the magnetic monopole situation. We expect monopoles to have a mass in a range predicted by grand unification theories of about 10^{16} GeV or 0.02 micrograms. The monopole velocity may be expected to fall within the range of 10^{-2} to 10^{-4} of the velocity of light. This corresponds to the range of β of our galaxy with the respect to the local super cluster, the β of the solar system through our local galaxy, or the observed β of the earth through the 3K black body radiation field. Magnetic monopoles may become attached to nuclear particles possessing a large magnetic dipole moment, so that a magnetic monopole may arrive at the earth bound to a proton, or, in passing through the earth if not already bound to a nucleon, it might capture a heavier nucleus such as aluminum 27. Magnetic monopoles have been predicted to catalyze proton decay (the so-called Rubakov effect).

Limits to the flux of magnetic monopoles may be set by at least two effects. The Parker bound is a limit based on the observed magnitude of the galactic magnetic field and the rate at which it would be neutralized by monopoles and built up by galactic dynamo effects. The other limit comes from ascribing the missing mass of the Universe to monopoles. Second, one may argue that there is a limit on the magnetic monopole density for a given mass if monopoles accounted for the missing mass required for closure of the Universe. New limits on the flux of magnetic monopoles as a function of monopole velocity are indicated in Figure 4 where the Parker bound and missing mass limits for $M=10^{16}$ GeV are both indicated.

Experiments using helium filled proportional counters at the University of California, San Diego (HE 6.1-12) and by the Tokyo group (HE 6.1-1, 6.1-2) are indicated as well as underground measurements of the KGF group and the Baksan groups (HE 6.1-6, HE 6.1-11). The most stringent limit presented comes from the track etch technique in mica where the assumption made and the limit presented (HE 6.1-8), is that a significant fraction of the monopoles that penetrate the minerals containing the mica are bound to aluminum 27 nuclei. Without this assumption, the treshold for the mica track etch technique is not sufficient to detect single magnetic monopoles. Other monopole limits based on the lack of observation of nucleon decay cascades (the Rubakov effect) have been discussed but were not presented at this meeting. New detectors coming into operation or planned at the Homestake mine by the University of Pennsylvania group (HE 6.1-9), by the MACRO collaboration planning an experiment in the Italian Gran Sasso of tunnel (HE 6.1-4, 6.15), by upgrades of Kolar Goldfield dectectors HE 6.2-4), and by the University of California San Diego group were discussed.

I may conclude this discussion of magnetic monopoles by stating that, as of this conference, there is no evidence for magnetic monopoles.

NUCLEON DECAY

At this conference there was one session devoted to nucleon decay. One may legitimately question whether nucleon decay is an appropriate topic for a cosmic ray conference. In fact if nucleon decay were observed it would have profound cosmological as well as particle physics ramifications. However in principle there is no more reason to dicuss nucleon decay before a cosmic ray audience than the searches for

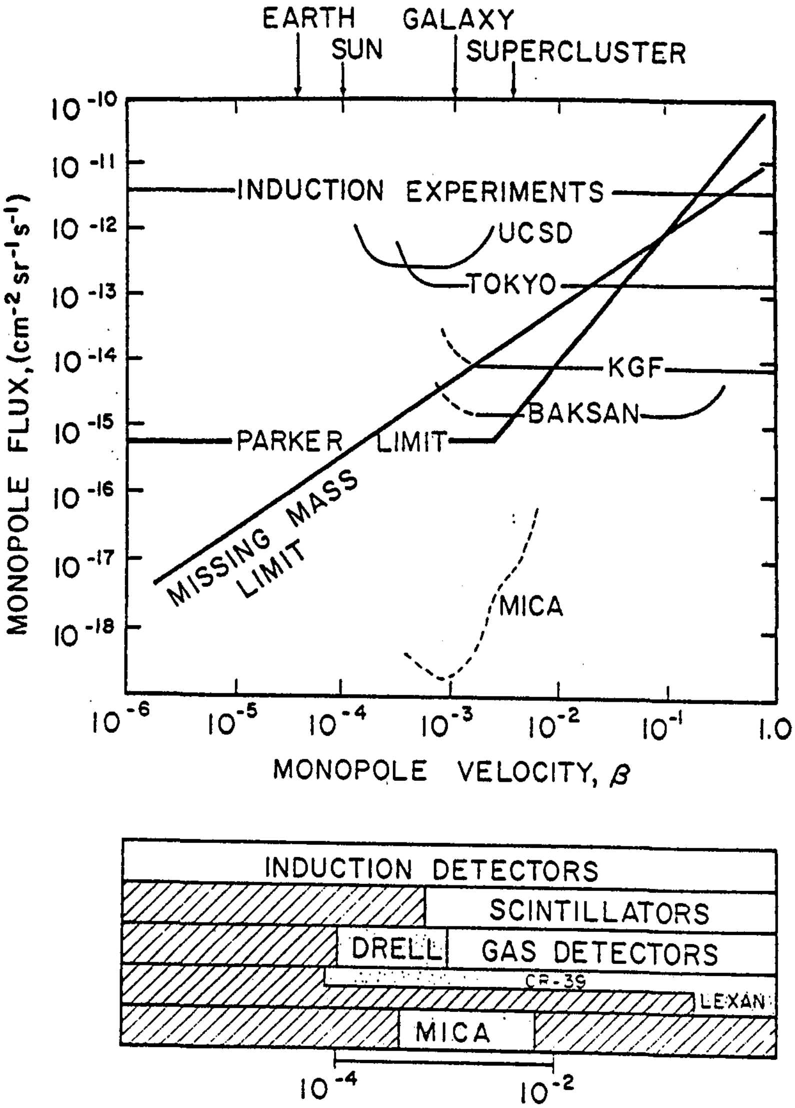

Figure 4. Monopole flux limits set by various experiments reported at this conference vs. monopole velocity, β. Also, noted are various astronomical velocities and, below the graph, the range of velocity sensitivity of various detectors.

neutrino mass, double beta decay, or parity violation in atomic hygrogen. Perhaps the reason that nucleon decay is discussed at a cosmic ray conference is simply the fact that many of the large nucleon decay experiments have been undertaken by cosmic ray groups.

Results were presented at this meeting by the Frejus group, (HE 6.2-2), the Nusex experiment (HE 6.2-6), the KGF group,(HE 6.2-3), and in a post deadline contribution by the IMB group. No report was presented here from the Kamioka experiment. Upgrades and new experiments were reported by the KGF collaboration (HE 6.2-4), and by the Minnesota Soudan group describing Soudan II (HE 6.2-5). A post deadline contribution describing the proposed MACRO experiment was presented, although information on the upgrades of the IMB detector and the Kamioka detector was not in the program. Table III reports the current limits on proton decay partial lifetimes corresponding to different decay channels as reported by the most sensitive detector operating, the IMB detector. Listed here are only proton decay limits. Comparable limits exist for the decay of bound neutrons.

The conclusions of the session can be stated at follows: Each experiment sees proton decay candidates among contained neutrino events. However there are no unambiguous candidates for proton decay, nor are there observed any statistically significant departures from the expected spectrum of neutrino interactions. The limits to proton decay can be summarized as follows: back-to-back decay modes such as $\pi^\circ e^+$ final states have a partial lifetime lower limit, $\tau/B \geq 10^{32}$ years (90% confidence level). Other modes involving K or μ final state particles have a partial lifetime limit, $\tau/B \geq 10^{31}$ years (90% confidence level). Recall that the prediction of minimal SU5 is that the proton lifetime should be about 10^{30} years with the decay going to $\Pi^\circ e^+$ about 60% of the time.

MISCELLANEOUS

Several reports were presented which I would group into a miscellaneous category. There was a report on massive hadrons in airshowers by the Maryland group (HE 6.2-7); the conclusion was that there is at this time no evidence for such particles in airshowers, in contrast with earlier reports. In another paper from Akeno negative evidence for tachyons was presented (HE 6.2-8) and tachyons seem now to be definitely gone. Wada claimed some evident for charge (4/3)e quarks in cosmic rays (HE 6.2-14), however I did not find the evidence compelling. Heinreich reported on a search for anomalons using CR-39 plastic etch detector (HE 6.2-12) with strong negative results. Finally, Yakovlev presented an argument for the explanation of the "long flying component" which he has previously reported from the Tien Shan experiment (HE 6.2-17). He argues that a cross section for charm production of serveral mb could explain that observation. It seems to me, however, that such a cross section is unrealistically large in the light of current accelerator data on charm production.

Table III. Proton Decay Partial Lifetime Limits
IBM 417 Day Results*

Decay Mode	Visible Cherenkov Energy	Detection Efficiency Including Corrections	Candidates† observed	Estimated background	Partial Lifetime Limit τ/B (10^{31}yr.) 90% C.L.
$e^+\gamma$	750-1100	0.66	0	0.2	36
$e^+\pi^\circ$	750-1100	0.46	0	0.2	25
e^+K°	300-650	0.12	7	8	7.7
	750-1100	0.14	0	0.5	
$e^+\eta^\circ$	400-650	0.07	5	6	20
	750-1100	0.37	0	0.5	
$e^+\rho^\circ$	200-500	0.16	6	6	1.7
$e^+\omega^\circ$	300-600	0.19	6	7	3.7
	750-1100	0.05	0	0.5	
$\mu^+\gamma$	550-900	0.52	0	0.2	28
$\mu^+\pi^\circ$	550-900	0.32	0	0.2	10
μ^+K°	150-500	0.19	7	7	4.0
	500-900	0.14	4	6	
$\mu^+\eta^\circ$	200-400	0.12	4	5	4.6
	550-900	0.23	2	1	
$\mu^+\rho^\circ$	150-400	0.10	4	5	1.6
$\mu^+\omega^\circ$	200-550	0.18	8	8	2.3
	650-900	0.03	1	0.7	
νK^+	150-375	0.08	6	11	0.96
$\nu\rho^+$	300-600	0.07	6	7	0.84
νK^{*+}	250-500	0.08	7	11	0.96
$e^+e^+e^-$	750-1100	0.93	0	0.5	51
$\mu^+\mu^+\mu^-$	200-425	0.58	1	0.7	19

*G. Bleuitt, et al., Phys. Rev. Letters 55, 2114 (1985).

†Many observed events are candidates for more than one decay mode.

DISCUSSION

By way of conclusion, I would like to make a few remarks on this area of cosmic ray physics. I would observed that the results of cosmic ray experiments as they pertain to high energy or elementary particle physics are not always taken seriously by high energy physicists working with particle accelerators, and it is appropriate to ask why.

In the first place, since about 1960 cosmic rays physicists have made several significant discoveries. The cross section of protons on air nuclei as interpreted from airshower data was first observed to rise as a function of energy by cosmic ray physicists and this was later confirmed at particle accelerators. The systematics of the nucleon-nucleon reaction were first studied extensively with cosmic rays, well before particle accelerators provided the same class of data with much greater precision. Thus the behavior of average multiciplicity versus energy, average momentum as a function of energy, the distribution of secondary particles vs. rapidity, the observation of scaling in the forward region, the behavior of average multiciplicity vs. atomic number, multiciplicity distributions of NN reactions and so forth were all first studied with cosmic rays. Charm mesons were first observed in cosmic ray emulsion chambers and I believe that Dr. Niu properly deserves credit for their first observation, although with uncertainty of the final state particle identities he was unable to unambiguously determine the D-meson mass. The Brazil-Japan group at Chacaltaya first observed jets which are now seen so impressively in the CERN data from the proton-antiproton collider.

Nevertheless, there are ambiguous and unresolved phenomena, many of long standing, reported by our cosmic ray colleagues. These include the Centauro phenomenon, the Chiron events, the long-flying component, and many other single event and single experiment anomalies. Particularly disturbing is the fact that these puzzles remain year after year, conference after conference without definitive resolution.

However, even worse, cosmic ray physicists have made significant mistakes. Let me simply list a number of the cosmic ray mistakes reported over the last twenty years, the period over which I have been in attendance at the international cosmic ray conferences.

Table IV. Cosmic Ray Mistakes reported over the period 1965-1985

Anomalous muon production
Aleph particles
Free quarks
Proton-carbon cross sections rising rapidly with energy
Average multiplicity proportional to lns
Mandela particles
Tachyons
Magnetic monopoles
Super heavy quanta
Massive hadrons in air showers
Minicentauros
Anomalons

To be sure, many of these errors were corrected later within the cosmic ray community, and I agree that accelerator physicists and others have their own undistinguished catalogues of mistakes. Nevertheless, the listing above should be sufficient to remind us why our discovery claims are not always accepted at face value.

CONCLUSIONS

The conclusions I draw from the sessions reviewed here may be briefly stated:

- The proton-air inelastic cross section is becoming better determined, especially with Fly's Eye data, and is reported to be 540 mb at a mean energy of 5×10^{17}eV. This corresponds to a pp total cross section, σpp=122 mb, compatible with $\sigma\bar{p}p \propto \ln^2 s$.
- New CERN data at 900 GeV c.m. has expanded our knowledge of cross sections, multiplicity distributions, and other inclusive properties of nucleon-nucleon collisons. Of particular interest is the continuing increase in 2-jet events with energy, corresponding to hard scattering of nucleon constituents.
- New p-nucleus data over energies from 30 GeV to 40 TeV largely agree with superposition models.
- Nucleus-nucleus data, especially from the JACEE collaboration at energies above 1 TeV/nucleon, show unual effects and may provide the first evidence of quark-gluon plasma effects.
- There is no current evidence for physical magnetic monopoles.
- Proton decay has not been observed. There are some ambiguous events, but in any event the proton lifetime must be considerably longer than minimal SU5 predictions.
- Some effects and putative particles, previously reported, are now dead. Other enigmatic effects remain unexplained and ambiguous.