THE USE OF COSMIC RAYS TO STUDY PHYSICS IN THE RANGE 100-1000 GeV *

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Over the past two decades physicists have always had at least one generation of accelerators under construction, so that the time lag between major steps in energy was about five years. Currently, we are faced with a serious gap, in that no accelerator of over 100 GeV is yet begun. In view of the lengthening construction time scale it may be almost a decade before higher energies are available. This situation has prompted myself and others to re-examine the entent to which cosmic rays might permit some quantitative study of strong interactions in the range of 100 to 1000 GeV (1). Surveying the recent history of physics, it is apparent that a dichotomy has developed between cosmic ray physicists and accelerator users in the scale and sophistication of their respective research tools. If a cosmic ray experiment were launched on the scale, say, of the new generation of 4 meter hydrogen bubble chambers, e. g. a few million dollars par year, quantitative high energy physics could be done in an energy range otherwize inaccessible for some years to come. Together with the MURA staff and other physicists from Michigan, Wisconsin and Denver, I have explored the design of a mountain top cosmic ray experimental facility employing spark chambers, large magnets, and a liquid hydrogen target. We have also set up and run a small-scale feasability experiment on Mount Evans, Colorado this past summer.

We believe that a major cosmic ray experiment, in order to warrent significant time and money, should meet the following criteria. A liquid hydrogen target should be used in order to insure reactions on protons. Secondly the data collected on interactions should be well above energies now available with machines and of statistics comparable to a thypical bubble chamber experiment. We have set as a goal about 10^5 interaction per year of pions and protons of energy between 100 and 1000 GeV. Third, both incoming and outgoing particles from a reaction should be momentum analyzed to a few parcent or better, and angles should be well resolved in order to study invariant masses, momentum tranfers, etc., with reasonable precision. While not aiming for a resolution sufficient to distinguish missing masses to within a pion mass, we would hope to detect most neutral as well as all charged particles from a reaction. Fourth, it would be a very desirable if not necessary to distinguish positive pions from protons in the incident beam. From the known attenuation of cosmic rays in the atmosphere it is clearly very desirable to operate this experiment at the highest altitude; on the other hand it should be readily accessible to men and equipment.

The flux of cosmic rays at the top of the atmosphere is given in Table I (2). The attenuation meam free path is about 120 gm/cm^2, and the spectrum is given by:

$$\int_{E_o}^{\infty} N(E)\, dE \propto E_o^{-1,67}$$

At mountain top elevations and for energies above 100 GeV the ratio of pions to nucleons at a given energy is about 20 — 30%, although this ratio is quite uncertain.

As a result of the criteria enumerated above and the fluxes of cosmic rays, the proposed experiment developed as sketched in Fig. 1, with rates of interaction at mountain top elevation as noted in the table. The vertical scale is set by the lever arms required for angular and momentum resolution the horizontal scale is then determined by the solid angle-area product to reach the desired interaction rates. While Fig. 1 illustrates a somewhat earlier stage of our thinking, it is a useful guide to the overall concept.

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* Supported by the National Science Foundation and the U.S. Office of Naval Research, Nonr 1224 (23).

** John S. Guggenheim Foundation, Fellow.

The heart of the apparatus is a $1 \times 2 \times 5$ m^3 liquid hydrogen target. The " beam " defining portion of the apparatus consists of spark chambers, thin scintillation counters, a large magnet, and a matrix of gas proportional counters. The magnet as designed here would weigh 1500 tons, consume 10 megawatts of power (for conventional powering) with a magnetic field volume of $2 \times 3 \times 4$ m^3 at 16 kilogauss.

Each spark chamber should be capable of locating a track to an uncertainty of $\pm$ 0,25 mm in each gap, or to ± 0.05 mm if 24 gaps are used in each chamber. With the spacings given, this corresponds to an accurancy in the bending angle of $\pm\ 6 \times 10^{-5}$ radians. For a 300 GeV/c particle, the momentum resolution would be $\pm$ 1.5% corresponding to a maximum detectable momentum of 20 GeV/c. An additional spark chamber at the center of the magnet gap would further improve the momentum resolution by about a factor of two. The use of wide gap spark chambers or of sonic or electronic readout is being considered.' Our current feeling is that the desired resolution is most readily achieved with photographic data recording.

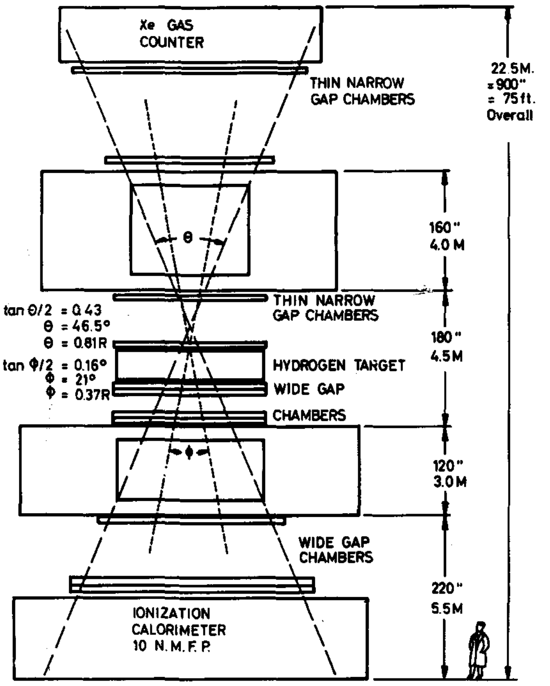

Fig. 1 - Outline of the proposed cosmic ray experiment for the study of strong interactions 100 - 1000 GeV. Not shown are gas proportional counters between spark chambers above the hydrogen target, spark chambers at the centers of the magnet gaps, and lead plate conversion spark chambers above the ionization calorimeter.

TABLE I

Acceptance and rates

Total solid angle $\Theta\ \varnothing = .81 \times .37 = .30$ sr.
Total target area $A = 9\ m^2$
Admittance $a = 1/4\ A\ \delta\Omega_1 =$ *0.68 m^2 sr.*

Cosmic Ray Fluxes (Y. Pal) in particles/m^2 sr. sec

Energy	Top of Atmosphere	At 14000 Feet (under 600g/cu² air)		
	87%p, 13%m	n + p	$\pi^- + \pi^+$	$\mu^- + \mu^+$
$\geq$ 100 BeV	7.0	4.6×10^{-2}	1.39×10^{-2}	—
$\geq$ 300 BeV	0.96	6.4×10^{-3}	1.92×10^{-3}	6.84×10^{-3}
$\geq$ 1000 BeV	0.10	6.7×10^{-4}	2.01×10^{-4}	3.74×10^{-4}

1 meter liquid Hydrogen target $\rho = 0.07$ g/cm^3
$N = 4.2 \times 10^{24}$ p/cm^2
for π^+ $\sigma = 25$ mb : $N\sigma = .105$
for p,n $\sigma = 40$ mb : $N\sigma = .168$

Interaction Rates at 14,000 feet 3600s/hr 8.75×10 h/yr

E	n + p sec^{-1}	per hour	per year
$\geq$ 100	5.25×10^{-3}	19	1.66×10^5
$\geq$ 300	7.3×10^{-4}	2.6	2.3×10^4
$\geq$ 1000	7.65×10^{-5}	.28	2.4×10^3
E	$\pi^- + \pi^+$ sec^{-1}	per hour	per year
$\geq$ 100	1.0×10^{-3}	3.6	3.15×10^4
$\geq$ 300	1.37×10^{-4}	.49	4.3×10^3
$\geq$ 1000	1.44×10^{-5}	.052	4.5×10^2

Total Trigger Rate for E $\geq$ 100 GeV/c about one every 3 minutes

In oder to separate pions from protons, the interstices between spark chambers would be occupied by gas proportional counters to measure in 10 — 20 separate samples the ionization. While the most probable ionization from a pion is 10% different than that from a proton at 300 GeV/c, the Landau spread is 15% (full width at half maximum), so that many independant measurements are necessary. From a more detailed study of this question, it appears that about 80% of the particles at 300 GeV/c can be reliably labeled. Below the target a similar magnet ($2 \times 2 \times 5$ m^3 field volume) and spark chamber array would serve to analyze emerging particles. Below the bottom thin-plate chamber a spark chamber of high-Z plates for γ-ray detection would be placed. The last element in the system would be an ionization calorimeter; an array of alternate layers of iron, ionization detectors, and spark chambers. Such a calorimeter is capable of $\pm 20\%$ determination of particle energy at 100 GeV and higher. The ionization detectors would

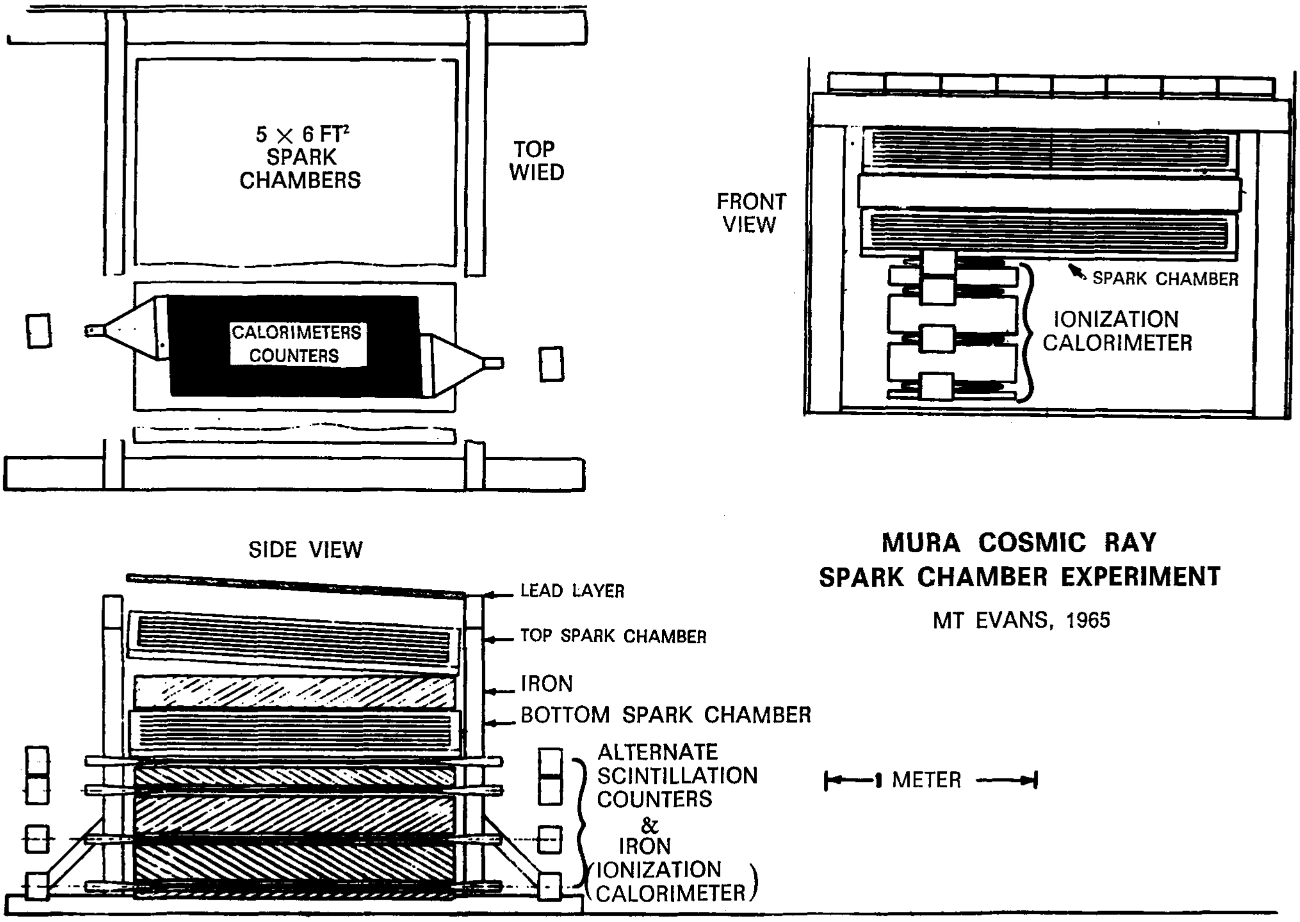

Fig. 2 - Drawing of the experiment run in August 1965 at 14,200 feet elevation to study possible background problems.

be scintillators in the top layers, serving as the primary triggering requirement for the system, and gas counters in the remainder.

The data from the experiment would consist of film from several cameras and pulse heights and/or timing information from about 2000 separate counter channels on magnetic tape. The analysis of this would probably be done at universities associated with the program using programmed-spot film readers and computer programs related to those currently used with analogous accelerator experiments. The system would trigger from the calorimeter on a total energy release of 100 GeV or greater in coincidence with an incoming particle through the hydrogen target. This would therefore record tracks independant of whether or not an interaction had occurred, permitting determination of total cross sections. The trigger rate would then be about one every three minutes.

The physics which could be studied with this experiment includes total cross sections, elastic scattering, isobar and resonant production, study of peripheral processes and the question of "fireballs" and associated phenomena noted by cosmic ray phisicists but beyond the range of current accelerator experiments. This experiment would be very effective in seeking quarks, and if found we would be able to explore their interactions. As examples, a year of continuous running would permit determination of total π^+ p, π^-p, and p p cross sections at 300 — 500 GeV to about 2% (limited by systematic uncertainties), and the slopes of the diffractions peaks of elestic scattering to about 4% in the same range. Over one hundred 10 TeV events per year would be seen, and at 100 to 200 GeV/c, the rate of pp interaction corresponds to about one microbarn-event per year.

The site which we believe is the most suitable compromise between nigh altitude and convenience is the summit of Mt. Evans, Colorado, at

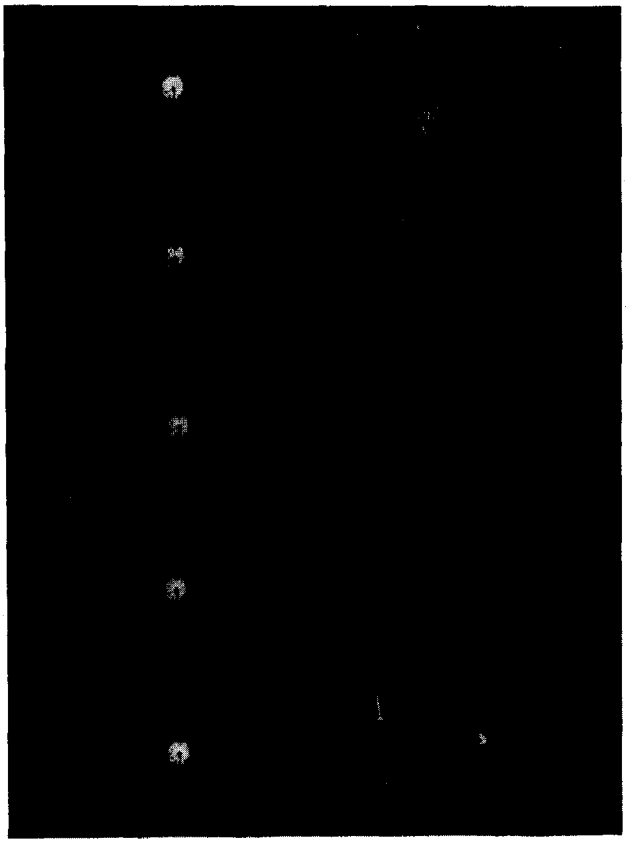

Fig. 3 - Sample photographs taken with the equipment sketched in Fig. 2, and a threshold of about 20 GeV. The photographs are of the « Front View » of Fig. 2, however the images are reflected so that the calorimeter is below the right side of the spark chambers on the film. The events are interpreted top to bottom as: a) a neutron interaction; b) an extensive air shower; c) an incoming particle producing a shower jet in the iron between chambers; d) a nair shower containing a jet; e) an incident pion or proton interaction in the iron.

14,250 ft. (under 0.62 of the atmosphere), accessible by automobile road, and a two hours' drive from Denver. This site is currently operated by the University of Denver and has been a site for cosmic ray research for many years. A study of this experiment indicates that it can be brought into operation in four years' time at a cost of about $ 15 million.

This proposed program is currently in the study phase, with no final dicision yet made on its full scale implentation. One serious question raised was the extent to which hadrons in the energy range to be explored were accompanied at close lateral spacings by other particles, in particular by soft showers. This would make analysis difficult or impossible if the spark chambers contained a high density of tracks unrelated to the particle or event of interest. In order to explore this question a small experiment was run on Mt. Evans this past summer. As illustrated in Fig. 2, it consisted of two 5×6 ft.^{2} spark chambers separated by about 8 inches of iron. A small ionization calorimeter permitted triggering on high-energy events (greater than 50 — 100 GeV) so that the photographs should reveal the distribution of accompanying tracks. While a quantitative analysis has not yet been completed, preliminary indications are that the majority of the events are clean, e. g. if detected in the proposed experiment they could be analyzed. Some early events are illustrated in Fig. 3.

It cannot be emphasized too strongly that we do not consider this program in any sense competitive with accelerators or storage rings of comparable energy. The event rate is too low and the nature of the information too restricted to compete with accelerators in any respect except time. For comparison, it can be noted that the phase space density of cosmic rays at 300 GeV at 14,000 feet is about 2×10^{-9} GeV^{-1} cm^{-2} sr^{-1} sec^{-1} while the corresponding figures for the CERN PS and AGS at 25 to 30 GeV is about 2×10^{21} Gev^{-1} cm^{-2} sr^{-1} sec^{-1}. This phase space factor of 10^{30} of course dictates the large phase admittance, 0.68 m^2 sr, of the proposed experiment. However the interaction rates here of the order of 10^{-3} per second correspond to rates of 10^5 per second for the proposed CERN storage rings or potentially 10^{12} for second with a 200-300 GeV synchrotron beam in a liquid hydrogen target. The comparison is less ridiculous for event rates typical with large bubble chambers in operation currently, e. g. 10^{-3} as compared to perhaps 10^{-1}. Considering the probable complexity of many events, it also seems that the analysis rate, together with physics interpretation of the results would only just keep pace with the data-taking rate using currently prevalent analysis techniques. We thus believe that the first results on the quantitative nature of high energy, strong interactions can be achieved with cosmic rays.

Physicists who have collaborated in this proposed experiment include F. E. Mills, C. Radmer, and others at MURA, U. Camarini, K. Symon, M. L. Good, R. H. March, and A. Subramanian from Wisconsin, D. I. Meyer from Michigan, and R. L. Chasson and M. Iona from Denver. The experiment this summer was conducted by members of the above group together with B. Dayton of Los Angeles. We should also like to thank O. Hoak, B. Loo, and J. Spooner for their technical assistance.

REFERENCES

(1) Earlier versions of this concept are presented in CERN AR/ Int SG/63-13 « A Cosmic Ray Experiment Design to Explore Strong Interactions at 300 GeV » L. W. Jones; BNL 1963 Super-High-Energy Summer Study AADD - 10 « Can Cosmic Rays Replace Accelerators? » L. W. Jones; and the Proc. of the Case Institute Conf. on Cosmic Rays, September 1964 (edited by F. Reines). Related projects of other groups using cosmic rays in neutrino physics, quark hunting, etc., are included in the latter reference.

(2) Y. Pal and B. Peters: Kgl. Danske Videnskab Selskab, Mat.-fys. Medd., *33* No. 15 (1964).