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A COSMIC-RAY EXPERIMENT AT NAL

I. Review of Current Problems

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I. Aims of Cosmic-Ray Experiment at NAL.

The primary aims of a cosmic-ray experiment at NAL are assumed to be:

1. To do a valid and interesting piece of physics research work, whose results are of intrinsic current interest and commensurate with the effort required, and which perhaps may develop in unexpected and serendipitous directions.

2. To get interesting physics going on the NAL site, so that we can help to create the atmosphere of a productive, active research laboratory and to establish a complete working viable NAL experimental group.

3. To enter into a field of research (ultra-high-energy physics), whose results will be related to our future work, and may perhaps even be helpful in designing experiments or facilities.

4. To acquire experience in methods and techniques that will be useful in experiments on the 200-GeV accelerator (e.g. acquiring and analyzing data from very complex events in large wire arrays; also, very high precision momentum measurements).

II. Current Problems in Cosmic-Ray Physics.

A. Categories of CR Research

To select a suitable area for cosmic ray work at NAL, let us consider the following categories, which are the ones used at the last international conference on cosmic rays at Calgary, Canada, in 1967:

1. Extensive air showers (EAS)
2. Muons and neutrinos
3. Origins and galactice phenomena
4. High energy interactions
5. Modulation

The first of these is concerened with the manifestation in the lower half of the atmosphere of the large showers produced by high-energy incident primaries near the top. Studies on muons and neutrinos are concerned with intrinsic properties of these particles, especially at high energies; with cosmological questions such as their galactic origin; and in the case of muons, which are unstable, with the extensive air showers in which they originate. Questions of origin and galactic phenomena include problems of cosmology, searches for primary electrons and gamma-rays, and the identification and measurement of incident primaries. High energy interactions refers to the study of the early part of a high-energy interaction - e.g. jets - at balloon and satellite altitudes. Modulation refers to studies of secular variation of cosmic rays - searches for direction anisotrophy, time variations, etc.

B. Currently interesting problems.

From the standpoint of NAL the first two of these categories seem the most immediately relevant; we need not exclude others if anyone gets a good idea, but we are better off not requiring satellite or balloon flights to begin with. If we accept this restriction, we find upon further inquiry that recent topics of current interest in these fields have included the following (among many others).

1. Studies in muon spectra at or near sea level, and underground, as a function of zenith angle.

2. Studies of energy losses by fast muons (over $\sim$ 100 GeV).

3. The distribution in space, time and energy of the muon component of EAS.

4. Comparison of observed EAS parameters with theoretical predictions.

5. Inferences concerning the primaries - spectrum, chemical composition, modulation - from observed properties.

6. Studies of rare and anomalous EAS events, such as "mu-poor" and "mu-rich" showers, and multiple-muon events.

Some of these topics raise rather basic questions in high-energy physics. For example:

1. Are there any significant sources of muons other than those already known, of which charged pion- and kaon-decay are the dominant ones? The (unconfirmed) experiments of the Utah group (Keuffel et al) are claimed [1-3] to

indicate that the zenith angle dependence of the muon spectrum indicates the existence of a hitherto unknown muon source, the "X-process". In it muons are generated either directly in a primary interaction or via short-lived intermediaries (i.e. $\leq 10^{-10}$ sec. lifetime). The Utah group attributes up to 2 percent of all muons (especially the high-energy end of the spectrum) to this process.[3)] These results, although unconfirmed,[4-6,31)] have been hailed as providing evidence for the eagerly sought, long-awaited intermediate vector boson.[7,8)]

2. If one constructs a Monte Carlo simulation of the air shower produced by an incident proton of 10^{12} to 10^{18} ev, one can obtain statistical prediction[9-11)] of the extent, direction, density and composition of the shower components, provided one extrapolates known yields, multiplicities, cross-sections, etc. to these stratospheric heights. The predictions may then be compared with experiments.[9,12-15)]

C. Status of some current problems in CR research.

Such comparisons have resulted in some interesting observations.

1. Lateral distribution of muons in EAS.

The lateral distribution of muons in large showers falls off more slowly than predicted, especially at high energies.[12,16,17)] This indicates that there may be some processes that result in unusually high transverse momenta; present estimates range from a few percent of muons with about 4 GeV/c[16)] to values of transverse momentum as high as 50 GeV/c.[10)] Some of these estimates may be suspect, because it is not always known sufficiently accurately what the direction and location of the shower core is; and sometimes the muon identification is impeachable.

2, Muon-rich and muon-poor showers.

In most showers the muon intensity bears a definite and preditable ratio to the soft component. Two kinds of anomaly are seen - mu-poor and mu-rich showers. In the former,[18-19)] the muon abundance is in agreement with that to be expected in a gamma-ray initiated cascade. The most likely origin is therefore electromagnetic. But the abundance of such events appears too high to be consistent with the observed upper limit for primary gamma-rays, which is of the order of 10^{-5} of the primary flux.

Muon-rich showers, containing too many muons,[20-21] are still unexplained; the hypothesis that ascribes them to heavy primaries appears unconvincing. They may perhaps represent events in which an exceptionally large fraction of the energy goes into charged rather than neutral pions.

3. Anisotropy of EAS.

Several claims have appeared for observing anisotropy in the direction of incidence of showers of one particular sort or another. These have usually disappeared with improved statistics,[22] and to date no good evidence for spatial or temporal anisotropy of the high energy primary radiation exists.

4. Energy loss of fast muons.

Date on the range-energy relation for fast muons, and on the differential energy loss dE/dx as a function of Absorber Z and muon energy, are incomplete. High energy muons lose energy via ionization, as modified by relativistic increases, and the density effect;[23] at very high energies, an additional source of energy loss, a term of the form

$$dE/dx = - b\ E$$

with b a constant (for air) near $4 \cdot 10^{-6}$ MeV/gm . cm^2, begins to outstrip the ionization loss.[24] This term is a bremstrahlung-type energy loss, characterized by a radiation length, and includes bremstrahlung, and also electron and muon pair production. At energies above 500 GeV/c, these terms become important, even dominant; and also very high-energy delta-rays can be produced that give rise to electromagnetic showers of appreciable size and extent.[25-26] The phenomenon of accompanying electromagnetic showers limits the usefulness of solid iron magnets as muon spectrometers to energies whose upper limit is about 1 TeV.[25]

The experimental status of the range-energy relation is not very satisfactory, and as a consequence the shape of the muon spectra observed, both at sea level and underground, remains clouded. Up to about 500 to 1000 GeV/c, measurements on muon spectra have been made with spectrometers; above this value, only from counting rates underground. Since the muon spectrum extends to at least 10^{17} ev., the conversion of underground counting rates to energy values requires knowledge not only of the range-energy relations, but also of the composition, thickness, density, and dE/dx of the overburden. Barton and Stockel[27] (Calgary MU-8) have compared the specgraphic and underground data in the region below 1000 GeV/c, where they are best. Important discrepancies (20% or more) occur even in the best spectrometer energy range (200 GeV/c and below), and also at high energy.

Because of almost inevitable uncertainties in the absorber composition, the derivation of the muon spectrum from underground measurements would be difficult, even if the range-energy relations were known perfectly. The situation is aggravated because of the very rapid fall-off of the spectrum at high energies. (See Fig. 1). It appears to be generally assumed that there are no uknown processes which attenuate high-energy muons by say, 50%, in passing through a mile of rock; this amounts to assuming no unknown processes of cross-section ca. 10^{-30} cm^2 per nucleon. For the verification of integral range-energy relations via known spectra it would appear that both good spectrometer measurements and reliable range measurements, either in highly undifferentiated terrain, or better still, in the ocean, are required. In addition, measurements of dE/dx as a function of both Z and E are needed.[33)]

III. Detailed Considerations of Some Interesting Muon Problems.

A. Muon Spectra at Sea Level. Direct Production?

Let us now consider the first topic: are there any extraordinary sources of muons? The intermediate boson is of course the Freudian motive of this question. The search for such a source is based on the following considerations.

1. Showers produced at large zenith angles α should contain increased numbers of high energy muons relative to vertical showers,[28)] approximately as $\sec\alpha$ in the limit of very high energies. This is because the number of very high energy muons is proportional to the decay path available to their parents, which is proportional to $\sec\alpha$ (at least near the top of the atmosphere, where it matters most).

A comparison of the abundance of high-energy (> 500-1000 GeV/c) muons at various zenith angles should therefore show this effect. If prompt production (via the postulated X-process) exists, the ratio of horizontal to vertical fast muons should be less than $\sec\alpha$.

2. Another feature of the muon spectrum produced by the increasing decay length is a change of slope of the muon spectrum. Suppose the parent pion (and kaon) spectrum has an energy dependence of $E^{-\beta}$ (for the integral spectrum, plotting all particles having an energy greater than E).

The muon decay averages about half the pion energy, and thus, if all pions have equal decay probability, the muon spectrum will have the same energy dependence as the parent pion spectrum. But now suppose the pions do not have equal decay probability, but equal path length before interaction; then the probability of decay of the faster pions will reduce as E^{-1}, and the resulting muon spectrum will go as $E^{-(\beta+1)}$. Since horizontal showers have available longer interaction paths, the change in slope from β to $\beta+1$ will occur at higher energies for horizontally incident showers than for vertically, and the "inflection" point should vary as $\sec\alpha$. Bergeson et al[3] point out that if we superpose on the pion and kaon sources of muons a "direct", i.e. short-lived source, we add a high energy muon component whose energy variation is only as $E^{-\beta}$, and which therefore must show up as a tail at very high energies even if it comprises only a small fraction of the total muon spectrum. The inflection point corresponding to the change of exponent from β to $\beta+1$ is readily observed and well-known[27,29]; the hypothetical residue of "direct" muon production has not been observed.

The Utah experiment measures the flux of muons underground as a function of zenith angle (from 45° up in the angular region 45° to 90°) and range (thickness of mountain). The ratio is obtained by using for the vertical intensity data obtained in other experiments, both at sea level and underground. Thus the conclusions are based on:

1. An assumed absolute vertical intensity vs. energy spectrum.

2. An assumed range-energy relationship up to ca. 10 TeV (to the extent necessary to make allowances for different kinds and densities of absorbers).

3. Assumed knowledge of the overburden - very detailed as to both thickness and composition in all directions - for several square miles of mountainous territory.

4. Assumed absence of unknown interactions of higher energy muons with cross-sections 10^{-30}/nucleon or more.

In designing a better experiment, all these uncertainties can be eliminated by measuring in a magnetic spectrometer both the vertical and the inclined spectra with the same equipment, to a sufficiently high energy. An indication of excess high-energy particles (no change of exponent in the muon spectrum) could be sought, preferably in the vertical spectrum. Such an experiment requires a spectrometer with a maximum detectible momentum (MDM) of 2-3 TeV or more.

Let us find the lower limit of the energy region in which the secα rule is expected to hold. For this condition to apply, the decay length of the pions and kaons, the parent particles, must at least equal or exceed the longest mean free path between pion interactions, so that the decay probability is proportional only to the parent path length. For the average vertical shower the first interaction takes place on the average in the first 80 g cm^{-2}, or above 18 km. The next interaction, another 80 g cm^{-2} lower, is about 4.5 km lower. 4.5 km is the decay length for 80 GeV/c pions, or for 620 GeV/c kaons. For horizontal incidence the corresponding interaction length in the atmosphere is about 32 km; this corresponds to the decay length for 0.6 TeV pions, or 4.4 TeV kaons. Thus at vertical incidence, the number of muons from pions or momentum above 0.08, kaons above .6 TeV will be depressed by the unavailability of decay path; for horizontal incidence the energies are correspondingly higher. The average muon from pion decay has about half the pion energy, so that the ratio of horizontal to vertical intensity for pion-decay muons should start to rise at about 40 GeV/c, and reach its full value at about 300 GeV/c. For muons decended from kaons, the numbers are 300 and 2200 GeV/c. In principle this is a way in which the K/pi ratio is v ery high energy production could be measured; there should be two distinct tails.

B. Vertical Intensity of Muons.

The counting rates depend upon the apertures of the equipment. For vertical incidence, an aperture of 1 m^2-sterad will record an intensity of about 1.1 muons/hr' of 1 TeV and above (see Fig. 1); at 5 TeV this is down to 1.1 per day. In any high-momentum spectrograph, attempts to obtain high momentum must be accompanied by increases in aperture as well.

The largest spectrograph now working (out of perhaps 7 or 8 now working or in construction) is the large Durham instrument, with a MDM of 5 TeV, weight of 200 tons, acceptance of .12 m^2-ster.

C. Energy Losses of Fast Muons.

As we have indicated, not many direct measurements of dE/dx for fast muons are available. The best existing data are found in the following reports.

1. Summary: Hayman, Palmer and Wolfendale, Proc. Roy. Soc. 275,

2. Measurements to 11 GeV/c: Bellamy et al, HEPL report 511; Phys. Rev. in press.

3. Sheldon and Duller, Calgary Conference paper Mu-12, give the following references:
   a. S. Ozaki, J. Phys. Soc. Jap. Suppl. A-III, 17, 330 (1962).
   b. Creed and Wolfendale, N. Cim. 47, 786 (1967)
   c. Discussion of spectrometer difficulties: M. G. K. Menon and P, Eaman Murthy, Prog. Elem. Part. & C.R. Physics, 9, (1967). N. Holland.

Electromagnetic interactions of muons:

4. Ashton, Coats and Simpson, Calgary Conf. MU-20. Electromagnetic Interactions of High Energy Muons. - In a Fe absorber, muons from 34-520 GeV/c were studied with scintillators, flash tubes. Burst frequency agrees with theoretical predictions.
5. Kelly et al. Calgary Conf. MU-21. Muon Interactions in the Range 5-1000 GeV/c. - uses magnetic spectrograph.
6. Hodgson et al, Calgary Conf. MU-23. A comparison of theory and experiment on the photonuclear cross-section of fast muons.

It is clear that good measurements on dE/dx, and on the partial cross-sections for various interactions such as muon-pair and electron-pair air production and bremstrahlung will be of both intrinsic interest and practical value.

For this reason, one may omit further discussion of this subject, and assume that if any experiment that involves detecting muons of known momentum is set up, an auxiliary arrangement for studying the dE/dx of such muons will be desirable.

Energy losses in any material may be measured by a sampling technique, in which a multi-layered sandwich of absorber and scintillator is used, so that the scintillator samples the energy loss in the absorber. The scintillators must be thin compared to the range of the secondary electrons produced in the absorber for the sampling to be valid; this condition should offer little difficulty at high energy.

IV. Extensive Air Shower Experiments.

Extensive air showers (EAS) and jets are both aspects of very high energy nuclear interactions, the former after considerable cascade development in the atmosphere, the latter at or near the interaction point of the primary itself, high in the atmosphere or even above it. Studies of jets are of jets are handicapped by the need to place detection equipment at high altitudes; an orbiting laboratory, or a lunar laboratory may offer the best ultimate platform for such work. Balloon and satellite work is handicapped by the fact that equipment adequate to the experimental requirements at very high energy is generally very large and very sophisticated; cf. the multiparticle spectrometer systems suggested for the 100 GeV/c range at NAL.

EAS studies, which observe the nuclear cascade at mountain elevations and blow, are concerned with the degradation products of the cascade. At full development, the shower will contain muons, neutrinos, positrons, electrons and gamma-rays; in the earlier stages of the shower there will also be hadrons; depending on the shower energy, some of these may survive to sea-level. The muons arise from pion and kaon decay, and thus tend to be produced more copiously at high altitudes, where the path length between interactions is longest. (See discussion on pp. 6-7). Since the muon spectrum thus represents a superposition of the pion and kaon spectra, let us consider what can be learned from its shape and spatial distribution.

1. Studies of shower parameters: for a given shower energy, how does the muon spectrum vary with distance from the core? better still, can we identify muons produced at various stages of the cascade, and so measure the spectrum as a function of depth in the cascade? This would yield a pion spectrum as a function of depth. Present data seems to indicate an excess of high-energy muons at large distances from the shower core.[10)]

2. Is it possible to distinguish muons from pi-decay from muons from K-decay? present methods are very indirect, involving analysis of showers to obtain the neutral pion spectrum, then assuming the neutral and charged pion and kaon spectra are identical; obtaining muon spectrum predictions for all pions and all kaons, and then interpolating

between these to obtain the mixture that best agrees with the observed spectrum.

3. There are several observations that appear difficult to understand. In addition to the anomalous zenith-angle dependence for high-energy muons found by Keuffel et al, which leads to the postulation of an "X-process" of prompt muon production, there are other oddities.

Extensive showers frequently show the presence of multiple cores of electrons. If these cores are taken to represent the development of showers due to single particles, their angular separation allows an estimate of their original transverse momentum. If the cores are assumed due to single hadrons, these must in some cases have transverse momenta as high as 100 GeV/c. If the cores are due to multiple particles with nearly identical direction, the transverse momenta required will be much less. The two cases can be distinguished by looking for the infrequent high-energy high-transverse-momentum muon that will be the occasional result of decay of a single particle with high transverse momentum; it will not exist if the cores are due to multiple jets.

We have already discussed the apparent presence of anomalously high transverse momenta, and of anomalous shower types. (See p. 3).

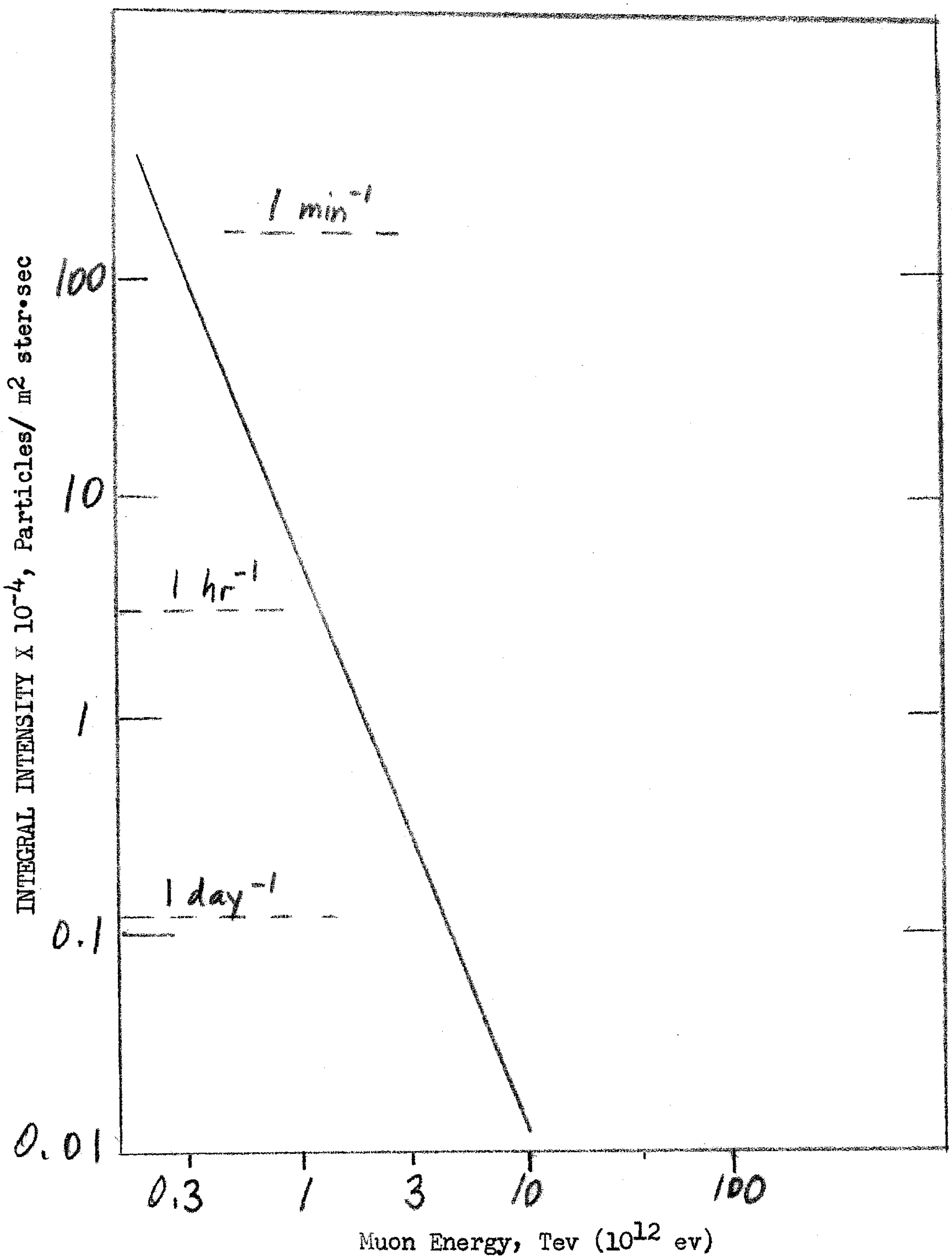

Fig. 1. Integral Muon Spectrum at Vertical Incidence at Sea Level. Slope $E^{-2.541}$

A COSMIC-RAY EXPERIMENT AT NAL

II. A Basis for an Experimental Proposal

A. Roberts

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In Part I we mentioned some of the problems in cosmic-ray physics which seemed both interesting and appropriate for an NAL experiment. In Part II we will outline a possible interesting experiment, and a possible procedure for arriving at a position from which it could be undertaken, via successive intermediate stages of expanding and profitable development.

The most obvious experiment of all is the verification or disproof of the Utah results, by direct measurement of the zenith angle dependence of the muon spectrum at 1000 GeV/c and above. This requires only a muon spectrograph; in addition every other AEC high-energy laboratory is preparing to do this experiment (viz. Voyvodic et al at ANL, Adair et al at BNL, Stevenson at LRL, Toner and Flatte at SLAC, Chen at PPA, plus Masek at UCLA). Some of these are considerably further along than we are. Consequently it would be well, in setting up a spectrograph, to consider other possible uses.

I. Illustrative Experiment to Measure Transverse Momenta of Muons

For the sake of illustration, we will design an experiment to measure the transverse momenta of individual muons in a high-energy EAS; most experiments to date have measured only statistical samples, not individual particles, with limited accuracy

In particular, muon spectrographs have not been used much in the study of EAS, especially above 100 GeV/c; and no one seems as yet to have attempted to use the potentially very high directional accuracy of spark chambers to reconstruct the trajectories of particles for the purpose either of reconstructing the shower "tree" or to determine individual particle transverse momenta.

If we consider muons of, say, 100 GeV/c or more, they will differ in direction from their parents only slightly, and their directions, corrected for magnetic deflection, may be used to indicate the parent pion direction. To determine the transverse momentum one must then

1. Determine accurately the fast muon direction (hopefully to 0.1 mrad.) and momentum, using spark chambers and a magnetic spectrograph.

2. Locate the shower core intersection with the ground, (using the electron density as measured in scintillation counters), and the direction of the core; together with (1) this yields the transverse momentum directly. However, to date the accuracy with which the direction of a shower core can be determined (by accurate timing, using Cerenkov counters) seldom reaches $\pm 2°$. Consequently this error will be the limiting factor in determining the transverse momentum; the location of the intersection with the ground is not difficult. Major effort must be directed toward improving this accuracy.

One should also note that the higher the fast muon momentum the closer it is likely to be to the core, so that very widespread high-energy muon detectors are not required. However, should we be able to detect one or more additional fast muon directions accurately, it should become possible to extrapolate back to the central "tree" of the core. This should be an accurate technique, limited only by the low probability of seeing more than one fast muon in a shower. On the other hand a very large number of events is not needed.

II. Generating an Experimental Proposal

The following proposal outlines a possible procedure for getting an experimental effort under way. While it represents considerable thought on my part, it it intended primarily as a basis for discussion and modification, not as a polished accelerator proposal; it is a work of Art, not a work of art.

In making a definite proposal, I have thought it best to be guided by several boundary conditions, which I will now make explicit.

1. In view of our monumental lack of experience with cosmic rays, including a lack of "feel" for the basic numbers involved, it appears best to start with an effort

which will orient us in the basics, and in addition get us into a real, useful physics measurement. For this purpose, I suggest that we start by constructing a small muon spectrometer, of aperture $\sim 1\ m^2$ sterad., to go up to 1 TeV or somewhat above; that we use it first to measure the vertical muon spectrum, and then the zenith angle dependence of that spectrum. We will have in mind later versions and expansions that will allow us to get into the business of measuring the transverse momenta of high-energy muons in EAS.

The dimensions of such a magnet can be evaluated by assuming that the minimum detectible deflection (MDD) is $\alpha = 0.1$ milliradian.

Since $\alpha = \frac{30\ B\ \ell}{p}$, we find $B\ \ell = 3.3\ p$, with p in TeV, $B\ \ell$ in kg-m. A relatively modest magnet, say 15 kg-m, would then go up to 4 TeV MDM, and would be sufficient for most purposes. We note for future reference, that the magnet proposed for the 25-ft bubble chamber will have a diameter of about 28 ft (9 meters) and 40 kg. This leads to a MDM, for $\alpha = 0.1$ mrad., of 100 TeV/c.

An experiment with a magnet from 15 to 50 kg-m should include measuring the zenith angle dependence of the spectrum at least in the vertical direction and at angles of 70° or more, so that the $\sec\alpha$ dependence can be verified.

It is worth noting that at energies of 1 TeV and above, the possibility of appreciable energy losses via bremstrahlung and other radiative processes in iron becomes appreciable, so that very large iron magnets may not be practical unless means for taking into account such losses (which interfere with the muon identification) can be found. At higher energies, large aperture air-gap magnets will probably have to be used.

A diagram of the proposed initial spectrometer is shown in Figs. 1-2. In order to get started quickly, and to learn what kind of problems a muon spectrometer encounters, it is suggested that we use at first only wide-gap chambers with camera recording, and add wire-plane spectrometers and automatic digital data recording as soon as the apparatus can be designed and procured. The wire-chambers will give us the desirable automatic data features; the wide-gap chambers will assure us that we understand in detail the events we are recording. The magnet does not appear to be a major component from the standpoint of expense or difficulty; its size is determined mainly by the attendant size of the spectrometer elements necessary to obtain a sufficiently large solid-angle acceptance.

We omit from the discussion, as noted earlier, the auxiliary equipment for muon energy loss measurements; this is to be added as it is designed and prepared.

In a later stage of the experiment, it will become interesting to add equipment for determining the location and direction of the cores of large EAS with considerable precision, as described above. Other directions of research are also possible and are not foreclosed.

By reducing the initial setup to the simplicity of Figs. 1-2, we make it at least thinkable to get on the air within six months. From there on we can begin to play by ear. The initial setup can be even more drastically simplified; operations and testing can begin without the magnet, with only two wide-gap chambers and two scintillators.

III. Proposed Initial Specifications.

Let the upper and lower spark chambers consist of two-gap modules, of dimensions 5 ft x 6 ft each (or longitudinally divided into two halves, each 2.5 x 6 ft), each with two 10-cm gaps. These will run at voltages near 100 kv. The scintillation counter trigger at first may include simply a twofold coincidence between large flat scintillators, each 5 x 6 ft, the same as the spark chambers. If these were made of liquid several cm thick, the optical collection would be improved, and it might be possible to use some degree of pulse height discrimination to rule out large showers.

The initial setup should use a cheap camera like a Beatty-Coleman, with a motor-driven magazine, and should be set up to allow trying a variety of demagnifications ranging from 20 to 50, so that we can experiment with different formats; at a demagnification of 20, the two chambers together will give an image 20 by 75 mm., which would allow highly accurate location. Plane mirrors (inexpensive plate glass will do) can be used to fit the images onto the film. (This is need only after the chambers are in place in the spectrometer.)

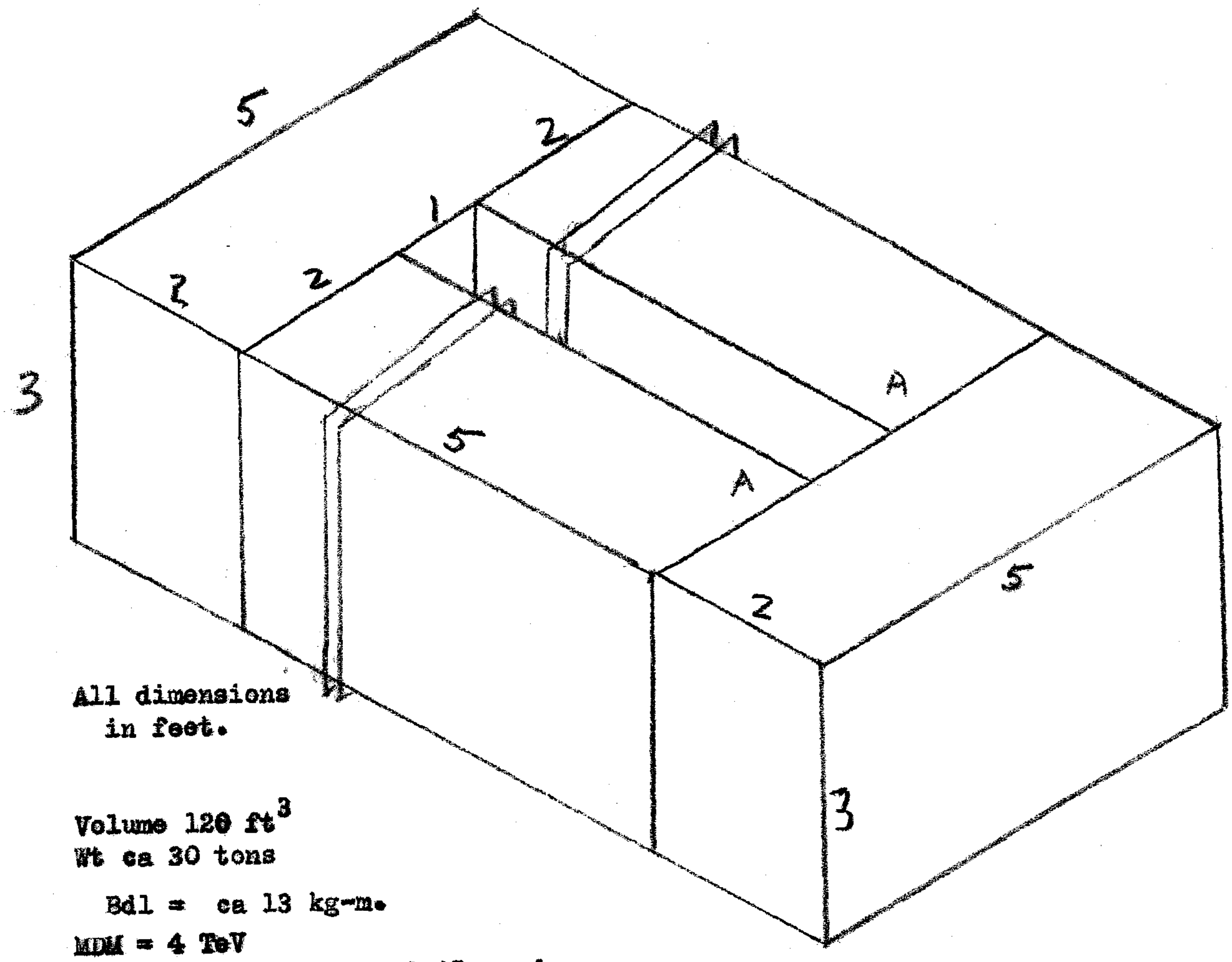
One of the first jobs to do is to verify the hypothesis that angular measurements of magnetic deviations to 0.1 mrad. are feasible. This should be tested with fast muons without a magnetic field.

Initial electronics: this will comprise

1. Magnetizing power for magnet
2. Electronics for scintillator counter coincidence
3. Spark chamber electronics, power supplies, Marx generators
4. Camera electronics.

Initial film readout and scanning equipment should include

1. Film developing equipment: small scale darkroom of our own, plus facilities for developing larger rolls (perhaps ANL?)
2. Projector for looking at short test strips (Recordak or similar).
3. Scanning machine facility available.
4. Measuring machine facility, of some sort, available.



All dimensions
in feet.

Volume 120 ft^3
Wt ca 30 tons

$\int$Bdl = ca 13 kg-m.

MDM = 4 TeV
Defl. Angle, 1 Tev = 0.45 mrad.
Geometrical aperture = ca 2 m^2 ster.
Counting rate, 1 Tev and above = ca. 2 hr^{-1}
Material : Reject low-carbon steel at $80/ton;
flame-cut, 8" or thinner slabs, overlapped in stacking
to avoid magnetic gaps.

Fig. [illegible]. Initial magnet, set up for vertical flux measurement. Only the two side arms (marked A) are used for deflection.

ACCEL.
[redacted] NATIONAL LABORATORY
ENGINEERING NOTES

PROJECT	DIVISION	SHEET
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SUBJECT Fig. 2. Elevation, C.R. Spectrometer

NAME A Roberts

DATE

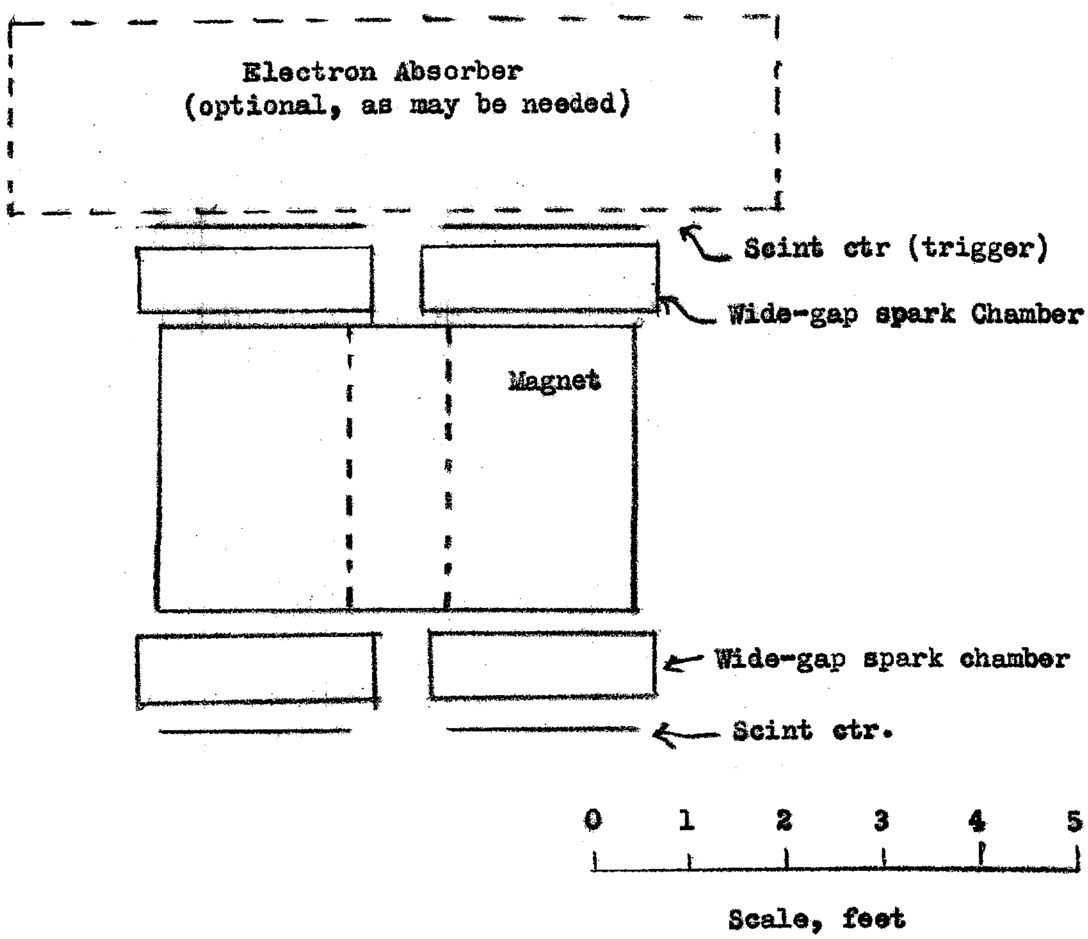

Fig. 2. Elevation view of spectrometer

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