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A COSMIC RAY PROGRAM FOR THE STUDY OF STRONG INTERACTION PHYSICS IN THE RANGE OF 100-1000 GeV

(Invited paper prepared for presentation at the
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A Cosmic Ray Program for the Study of Strong Interaction Physics in the Range of 100-1000 GeV*

Lawrence W. Jones
The University of Michigan

Since 1962 there have been continuing discussions on the possibility of erecting an ambitious cosmic ray experimental facility at mountain altitudes directed toward the study of strong-interaction physics in the energy range of 100 to 1000 GeV.[1] As the concept crystallized, we formulated several specific objectives for such a facility: (1) that nucleon interactions be studied on free protons, i.e., a liquid hydrogen target; (2) that the identity of the incident particle be ascertained and that momentum analysis of the incident and reaction products be precise to a few percent; and (3) that the total number of events collected at energies well above existing accelerator energies be over 10^5 per year. In 1964 these thoughts were further developed at a small conference in Cleveland[2] and in 1965 they were presented to the government agencies for consideration and support.[3] We were encouraged to study the technical and scientific questions encountered in the design of such a facility, and over the past two years the National Science Foundation has supported us in a program of feasibility study. Before presenting our present concept of this research

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facility, I would like to review some highlights of this interim program.

A major concern in the design of an experiment for a mountain top location was the extent to which energetic cosmic ray hadrons were immersed in a flux of accompanying particles, e.g., air showers. Accordingly, in 1965 a small experiment was operated at the summit of Mt. Evans, Colorado, in order to study this question. Two spark chambers of 5x6 ft^2 were located above a small ionization calorimeter of 2x4 ft^2 area and triggered on calorimeter signals corresponding to incident hadrons of over 50 GeV. The spark chamber photographs were analyzed in terms of the minimum radial separation between the hadron and other particles as function of energy. The results are presented in Figure 1, from which it is apparent that the problem of accompanying particles is not serious at 100 GeV and is sufficient to reduce by one third the useful number of hadrons of several hundred GeV if accompanying particles beyond half a meter may be tolerated. The aboslute flux of hadrons as a function of energy was also determined and found to be consistent with other measurements.

In 1966 a larger apparatus was operated with the dual objective of studying further technical questions relating to the major proposed facility and of searching for massive, elementary particles (e.g., quarks). This apparatus contained an ionization calorimeter of 3x6 ft^2 area and 1100 gm/cm^2 of iron, a 40x80 in^2 wide-gap spark chamber, 6 layers of gas proportional counters, and an array of 130 ft^2 of shower-detecting scintillation counters around the perimeter of this central stack. This system is shown in Figure 2. The results of the search for massive elementary particles is being presented separately at this conference.[4] Very briefly, the method employed a search for energetic events in the calorimeter delayed relative to accompanying air showers, as originally suggested by Damgaard _et al._[5] This method has the advantage of being independent of the particle charge. The aperture and operating period were sensitive to a flux of 2×10^{-11} particles per cm^2 sr sec. Including the possible attenuation of massive particles in the atmosphere and the probability of detecting an accompanying air shower, this flux figure is modified to about 4×10^{-10} cm^{-2} sr^{-1} sec^{-1}, although the exact figure depends upon various model assumptions. While one event was detected consistent with the expected behavior of a 35 GeV particle of 6.5 GeV/c^2 rest mass, there is also an 8% probability that this event was a nucleon. We thus do not regard this as significant evidence for existence of a massive elementary particle, but rather as setting an effective upper limit to the flux of such particles.

The experimental questions studied included the nature of cascades in the ionization calorimeter, the behavior of large wide-gap spark chambers in an experimental environment, and the use of gas proportional counters for particle identification. The results of the calorimeter study[6] are generally similar to those of Murzin,[7] Cowan,[8] and others. We find average attenuation length of 200 gm/cm^2 in iron for the ionization from an incident hadron, independent of incident energy (Figure 3). However, large fluctuations in ionization as a function of depth occur in individual events, as illustrated in Figure 4.

The wide-gap spark chambers, operated at voltages in excess of 100 kv, contained two gaps of 5 in. spacing and 40x80 in^2 area separated by a driven central 0.001" Al electrode. The shielding was such that this pulse was not noticeable in the output of the gas proportional amplifier electronics. As the most probable singly-ionizing particle pulse in the counter gave a signal of 10^{-14} coulombs on a 400 pF capacitance, the spark chamber pickup was equivalent to less than 5×10^{-16} coulombs input. A detailed study of a similar wide-gap spark chamber of 8 in. gap spacing in our laboratory has shown an achieved resolution of $\pm 10^{-3}$ radians in angle and ±150μ in space. These figures are limits set by multiple coulomb scattering of the cosmic-ray muons, the particles employed in the resolution studies; and the actual precision of the chambers is believed to be significantly better.

We have also extensively explored the use of a number of gas proportional counters to separate positive pions from protons at energies above 100 GeV.[9] We have learned that the distribution of ionization of such gas counters is about twice as broad as the Symon-Landau-Vavilov[10] prediction, but is in agreement with the calculation of Blunk and Liesegang,[11] wherein atomic binding effects are considered. From Monte Carlo calculations, we conclude that an array of 12 proportional counters of the sort used in the 1966 experiment could be used to separate 100 GeV protons in cosmic rays from positive pions using a maximum likelihood calculation applied to the separation pulse heights. The degree of separation is indicated in Table I.

We have also constructed a small superconducting magnet with 8" pole diameter to explore the problem of supporting the magnetic forces exerted by superconducting coils of Nb_3 Sn across the required thermal insulation. This realistically models the problem of replacing copper coils on a conventional iron magnet topology with superconducting coils contained in a "donut"-shaped cryostat. Results of this model program were very satisfactory in that the heat losses through a nylon support structure were reasonable and the mechanical forces at full, superconducting current were satisfactorily sustained.

This year we are constructing a new experiment at the Echo Lake station wherein we plan to measure the proton-proton total cross section in the range from 100 to 1000 GeV to a precision of from 5% to 20%. This will employ an expanded version of the system used in our 1966 experiment with the addition of a 2500 liter liquid hydrogen target. The system now under construction is illustrated in Figure 5. Besides statistics, the principal sources of error are uncertainty in the pion-proton ratio and the uncertainty in the ratio of elastic to total cross sections. We expect this system to be collecting significant data this autumn and to accumulate over 5000 interactions in the hydrogen target by nucleons of over 100 GeV within a 6 month period of operation.

The long-range goal of our group is to construct and operate a major facility at the summit of Mt. Evans. The system proposed is shown in Fugures 6a and 6b. It would contain a 10,000 liter liquid hydrogen target and two large magnets, each with an aperture of 9 m^2 and a bending power of 40 kilogauss-meters. The overall system would be 70 feet high and would employ 8 wide-gap chambers of the type we have built, but scaled to areas of 2x4.5 m^2 and 3x7 m^2. The primary trigger would be provided by an ionization calorimeter of 3.5x9.5 m^2 area and 1000 g/cm^2 thickness. Together with narrow-gap spark chambers, it would not only trigger the system at a certain energy threshold, e.g., 50 GeV, but would identify the energies and angles of neutral particles from reactions. It would also largely separate energetic γ-rays from neutrons. The momentum resolution would be about 3% at 400 GeV/c, and the resolution in angle achieved with the spark chambers (e.g., scattering angle, opening angle, etc.) would be $\pm 5 \times 10^{-5}$ radians. Two matrices containing a total of 22 horizontal layers of gas proportional counters in the incident "beam" would permit pion-proton separation. The spark chamber data would be photographically recorded, while the information from the proportional counters, calorimeter counters, and other scintillation counters would be digitized on magnetic tape with the aid of a small electronic computer. The magnets might be conventionally powered or superconducting. If conventional, they would require about 8.75 MW apiece. At this time the superconducting option appears most attractive.

It has become traditional that a discussion of a proposed new facility include a statement of the physics to be done. In the present case such a prognostication is particularly difficult, as the energy range to be explored is so far beyond current laboratory experience. Exactly the same problems are encountered in discussions of new accelerators.

The physics potential of the apparatus is apparent from Tables II and III where the appropriate fluxes, interaction rates, and yields for various strong interaction processes are noted. Total cross-sections and elastic scattering would be easily and accurately measured. Other known specific two-body final state channels would be quite uncommon, based on extrapolations from current accelerator data and fashionable theories. An exception would be those processes which proceed through exchange of the quantum numbers of the vacuum, or through diffraction dissociation. Here, cross-sections may be approximately energy independent, and such reactions as $pp \rightarrow pN^*(1512)$ may continue to be important up through 1000 GeV. Other processes which may be expected to contribute are boson exchange channels leading to a specific final-state resonance or particle at one vertex but integrating over all kinematically-available states at the other vertex. An example, $\pi^- p \rightarrow \rho^o N^*(\text{all})$ (where $N^*(\text{all})$ includes all final-state nucleon systems), experimentally demonstrates the one-pion-exchange prediction of an almost energy independent cross-section up to 18 GeV.[12] A particular subset of these processes may be those wherein a virtual exchange particle elastically scatters on the target particle, such as $\pi^- p \rightarrow \rho^0 \pi^- p$. If this "Deck effect" process[13] is correctly interpreted in recent accelerator experiments, it would also correspond to an almost energy independent cross-section.

These particular channels are cited as interesting subjects for study in the context of current results from accelerator experiments. We also believe that final state systems with the smallest number of particles (or resonances) may be the most readily interpreted theoretically, even though they are relatively rare. On the other hand, such questions as fireball production, studies of correlations, and statistical questions in many-particle final states will be carefully explored with high statistics and precision. As an example, a detailed study of the transverse momentum distributions of secondaries would be very valuable for comparison with recent results of Krisch _et_ _al_. at accelerator energies.[15]

This project is being pursued in the context of intense international interest in high energy strong interactions. Thus the Serpukov 70 GeV synchrotron is nearing completion, the CERN ISR is under construction, and the U.S. 200 GeV National Accelerator Laboratory is being organized. Against this backdrop, this facility will represent a unique source of data on pion-nucleon interactions above 200 GeV for a long period, even though there may be significant overlap between this program and the CERN ISR in proton-proton physics. In addition, np reactions and studies of the A-dependence of reactions (coherent effects), can be studied above 200 GeV. There will be a significant number of energetic muon events per year, and, while the triggering is more difficult, the possible results could be very interesting.

Support and financing of the facility described here is being requested at this time. It will require four years construction time at a total cost of about $23 million.

The logistical questions in establishing this mountain top station, while formidable, all appear soluble. The architect-engineering firm of Skidmore, Owings, and Merrill have studied the costs in constructing a permanent laboratory building of about 50,000 ft^2 floor area at the summit of Mt. Evans, and find that a total cost of $5 million would be sufficient. A 300 Megawatt pumped-storage facility of the Colorado Public Service Company is located 7 miles overland from our proposed site, and the U.S. Forest Service and power company engineers have agreed on a routing for a 115 kV power line capable of handling a 25 MW load. The Colorado State Highway Commission engineers have appraised the costs of improving the highway to the summit and of maintaining it clear of snow for year-round access. If conventional magnets are used, a closed glycol cooling system would be employed with air cooling. Other logistical questions such as water and liquid hydrogen supply have been satisfactorily solved.

This presentation would be incomplete without crediting my colleagues in this program, Fredrick F. Mills of The University of Wisconsin and Bruce Cork of the Lawrence Radiation Laboratory. We have been most fortunate in the participation in our program of P. V. Ramana Murthy and A. Subramanian, on deputation from the Tata Institute. Scientists also playing important roles in this program have included D. Lyon, D. Pellett, R. Roth, B. Loo, and G. DeMeester (Michigan); R. Hartung, R. Reeder, R. March, and S. Mikamo (Wisconsin); E. Marquit and A. Benvenuti (Minnesota); B. Dayton (Los Angeles); A. Bussian (H.A.O., Boulder); P. Kearney (Colorado State University); and S. Snowdon, G. DelCastillo, R. Fast, W. Winter, C. Radmer, and J. Hicks (M.U.R.A.).

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13. R. T. Deck, Phys. Rev. Letters 13, 169 (1964).

14. L. Stodolsky, Phys. Rev. Letters 18, 973 (1967).

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Table I

Proportional Counter Study:

Separability of protons and pions in an
array of 12 proportional counters by
the likelihood ratio method with enhanced widths

To Select Proton Beam

L	>1.0	>3.0	>5.0	>8.0
ϵ_p	83 %	60.7%	50.3%	40.7%
ϵ_π	19.2%	6.0%	3.4%	1.8%
Contamination	6.5%	2.9%	2.0%	1.3%

To Select Positive Pion Beam

L	<1.0	<0.5	<0.3	<0.1
ϵ_p	14.1%	6.9%	3.7%	0.5%
ϵ_π	78.4%	60.1%	48.1%	19.1%
Contamination	37.4%	27.8%	20.6%	8.3%

These efficiencies and the π^+/p ratio (≈ 0.3) in the cosmic radiation would imply a certain amount of contamination by the wrong kind of particles whose values are given in the 4th row.

Table II

A. Hadron Flux at 14000 ft. Particles per m^2 sr sec

E(BeV)	Total	Ratio $\frac{\pi^\pm}{p}$	p	n	π^+ and π^-
>100	$2.65\text{x}10^{-2}$	0.5	$1.05\text{x}10^{-2}$	$1.05\text{x}10^{-2}$	$0.55\text{x}10^{-2}$
100-300	$2.25\text{x}10^{-2}$	0.5	$0.90\text{x}10^{-2}$	$0.90\text{x}10^{-2}$	$0.45\text{x}10^{-2}$
300-1000	$3.2\ \text{x}10^{-3}$	0.65	$1.2\ \text{x}10^{-3}$	$1.2\ \text{x}10^{-3}$	$0.8\ \text{x}10^{-3}$
1000-3000	$3.5\ \text{x}10^{-4}$	0.65	$1.3\ \text{x}10^{-4}$	$1.3\ \text{x}10^{-3}$	$0.9\ \text{x}10^{-4}$

B. Hadron Flux through 0.55 m^2 sr per sec

E(BeV)	Total	p	n	π^+ and π^-
>100	$1.46\text{x}10^{-2}$	$5.8\text{x}10^{-3}$	$5.8\text{x}10^{-3}$	$3.0\text{x}10^{-3}$
100-300	$1.25\text{x}10^{-2}$	$5.0\text{x}10^{-3}$	$5.0\text{x}10^{-3}$	$2.5\text{x}10^{-3}$
300-1000	$1.76\text{x}10^{-3}$	$6.6\text{x}10^{-4}$	$6.6\text{x}10^{-4}$	$4.4\text{x}10^{-4}$

C. Target Interactions: assuming $\sigma_{NN} = 40$ mb, $\sigma_{\pi N} = 25$ mb

E(BeV)	pp or pn		π^+p and π^-p	
>100	$9.3\ \text{x}10^{-4}\ \text{sec}^{-1}$	$2.9\text{x}10^{4}\ \text{yr}^{-1}$	$3\ \ \text{x}10^{-4}\ \text{sec}^{-1}$	$9.5\text{x}10^{3}\ \text{yr}^{-1}$
100-300	$8.0\ \text{x}10^{-4}\ \text{sec}^{-1}$	$2.5\text{x}10^{4}\ \text{yr}^{-1}$	$2.5\text{x}10^{-4}\ \text{sec}^{-1}$	$7.9\text{x}10^{3}\ \text{yr}^{-1}$
300-1000	$1.05\text{x}10^{-4}\ \text{sec}^{-1}$	$3.2\text{x}10^{3}\ \text{yr}^{-1}$	$4.4\text{x}10^{-5}\ \text{sec}^{-1}$	$1.4\text{x}10^{3}\ \text{yr}^{-1}$
1000-3000	$1.15\text{x}10^{-5}\ \text{sec}^{-1}$	$3.6\text{x}10^{2}\ \text{yr}^{-1}$	$4.9\text{x}10^{-6}\ \text{sec}^{-1}$	$1.5\text{x}10^{2}\ \text{yr}^{-1}$

D. Interactions within the Target and Fiducial Solid Angle per Microbarn per Year

E(BeV)	pp	np	π^+p	π^-p
>100	.73	.73	.19	.19
100-300	.63	.63	.16	.16
300-1000	.08	.08	.028	.028
1000-3000	.009	.009	.003	.003

Table III

Rates for Various Reactions

A. Reactions predicted to be approximately energy independent

Process	Cross Section	Events/year >100 BeV	>300 BeV
1. Elastic scattering			
π^+p	4 mb	760	100
π^-p	4 mb	760	100
pp	8 mb	5800	
np	8 mb	5800	
2. Elastic scattering with $\lvert t \rvert < 0.01$ $(\mathrm{BeV}/c)^2$ (region sensitive to Coulomb-Nuclear interference and hence for the real part of the scattering amplitude)			
π^+p	0.3 mb	35	4
π^-p	0.3 mb	35	4
pp	0.75 mb	550	70
3. Production of Isospin $\frac{1}{2}$ nucleon isobars N^* 1520, 1690, and 2190			
$pp \rightarrow pN^{*\frac{1}{2}}$	1.0 mb	700	100
4. Production of ρ^0 meson integrating over final states at the nucleon vertex			
$\pi^-p \rightarrow \rho^0 N^*$(all)	0.5 mb	100	12
5. Deck effect or production of the A_1 boson			
$\pi^-p \rightarrow \pi^-\rho^0 p$	0.1 mb	20	2
$\pi^+p \rightarrow \pi^+\rho^0 p$	0.1 mb	20	2

Table III (continued)

B. Meson Exchange Reactions

	Energy Dependence of Cross Section $\sigma\ s^{-N}$	Cross Section at Energy	Events per Year over 100 BeV
	N	σ E	
1. $pp \rightarrow pN^{*3/2}$ (π exchange)	1.3	100 μb at 15 BeV 8 μb at 100 BeV	5
2. $\pi^- p \rightarrow \pi^0 n$ (ρ exchange)	1.3	25 μb at 18 BeV 4 μb at 100 BeV	1
3. $\pi^- p \rightarrow K^0 \Lambda^0$, $K^0 \Sigma^0$ (K^* exchange)	1.4	140 μb at 4 BeV 15 μb at 100 BeV	2
4. $\pi^+ p \rightarrow N^{*++} \pi^0$	1.1	1.1 μb at 1 BeV 7 μb at 100 BeV	1
5. $\pi^- p \rightarrow \rho^0 n$ $\pi^- p \rightarrow \rho^- p$ $\pi^+ p \rightarrow \rho^+ p$	1.5	600 μb at 4 BeV 4.8 μb at 100 BeV 450 μb at 4 BeV 3.6 μb at 100 BeV 375 μb at 4 BeV 3 μb at 100 BeV	1-2

FIGURE CAPTIONS

Figure 1. The radial distribution of the nearest accompanying particle as a function of total energy from the 1965 M.U.R.A. experiment on Mt. Evans. The ordinate is the probability of occurrence of an accompanying particle within a radius of R meters of the detected energetic hadron.

Figure 2. Design of the 1965 Echo Lake experiment to search for massive, elementary particles and to explore the properties of proportional counters, wide gap spark chambers, and the total absorption spectrometer.

Figure 3. Averaged shower curved for some selected energy bins.

Figure 4. Individual event shower development in the total absorption spectrometer. The curves are drawn only to guide the eye. The X's are the actual data points.

Figure 5. Design of the 1967 Echo Lake experiment for the determination of total cross sections over the energy range 100-1000 GeV.

Figure 6a. Front view of the overall experimental assembly. The overall height is 836 inches. The magnetic field is normal to the plane of this section. An extreme diagonal ray is indicated illustrating the aperture subtended ($\theta/2 = 21.8°$). The phase space admittance of the system is 0.55 m^2 sr.

Figure 6b. Side view of the overall experimental assembly. The overall height is 836 inches. The magnetic field is parallel to the plane of this section. An extreme diagonal ray is indicated illustrating the aperture subtended ($\varphi/2 = 8.7°$).

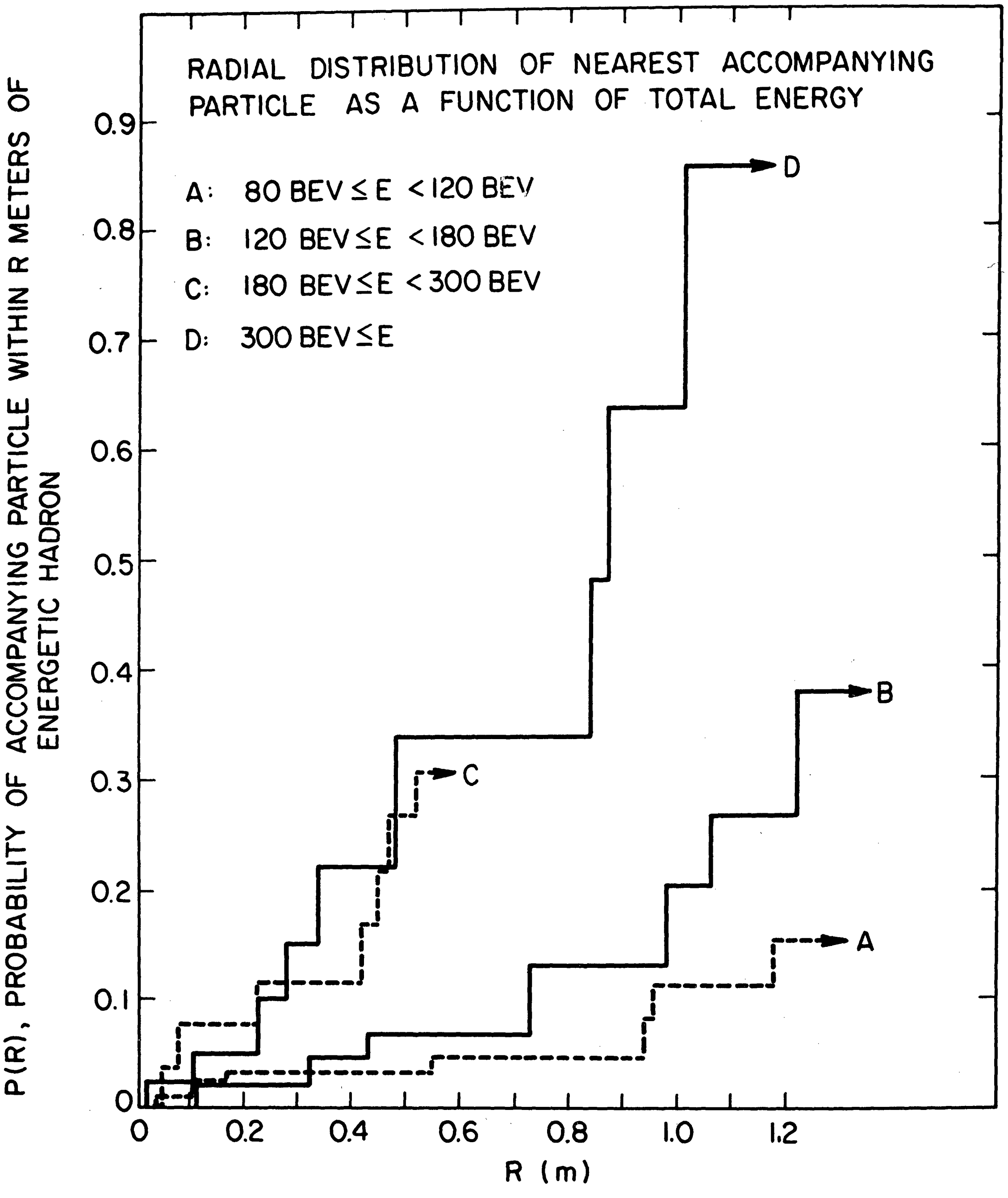
RADIAL DISTRIBUTION OF NEAREST ACCOMPANYING PARTICLE AS A FUNCTION OF TOTAL ENERGY
A: 80 BEV ≤ E < 120 BEV
B: 120 BEV ≤ E < 180 BEV
C: 180 BEV ≤ E < 300 BEV
D: 300 BEV ≤ E
P(R), PROBABILITY OF ACCOMPANYING PARTICLE WITHIN R METERS OF ENERGETIC HADRON
R (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.2
0.4
0.6
0.8
1.0
1.2
A
B
C
D

Figure 1

MURA COSMIC RAY EXPERIMENT

QUARK SEARCH AND LARGE EXPT FEASIBILITY STUDY 1966

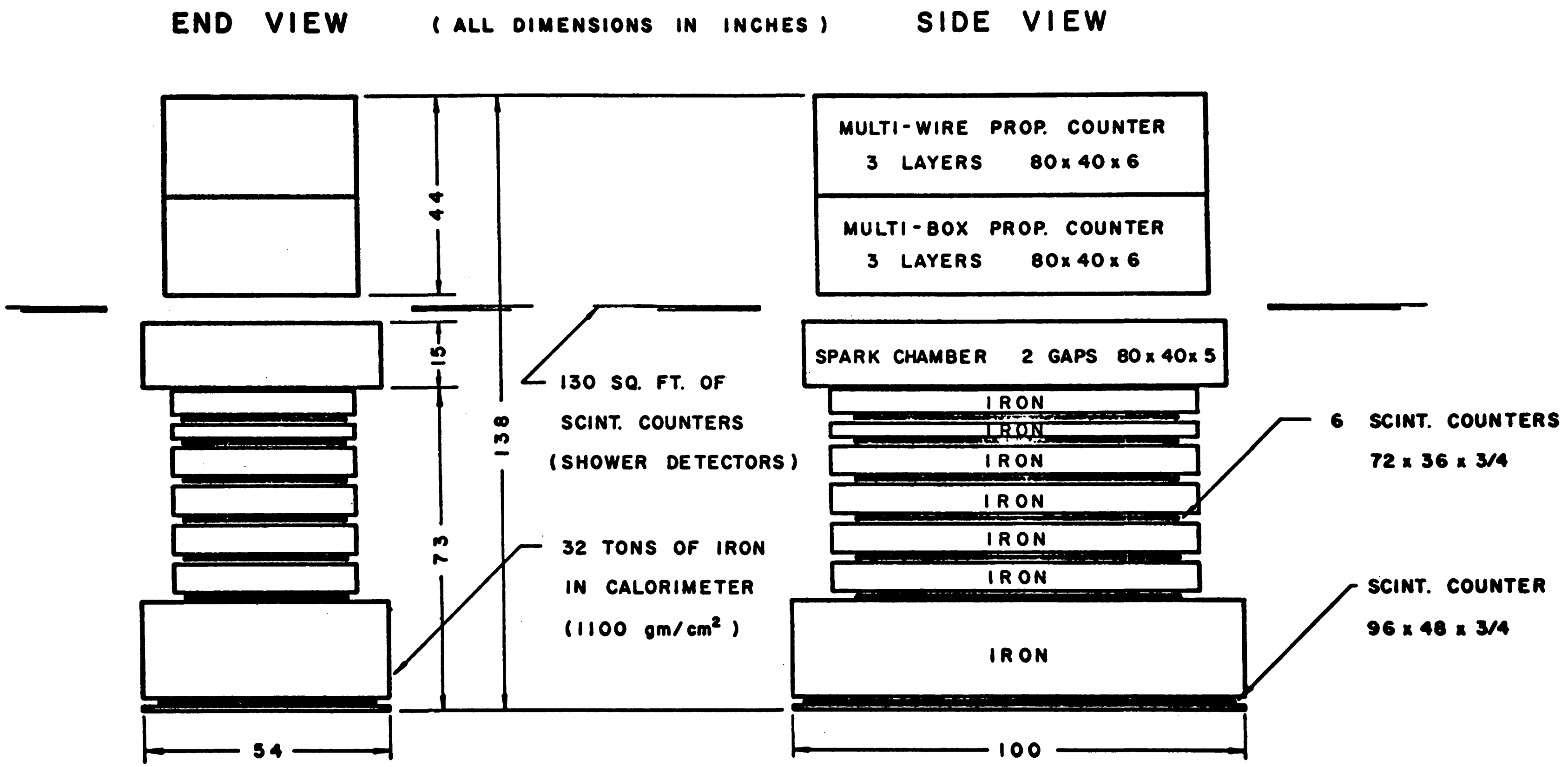

Figure 2

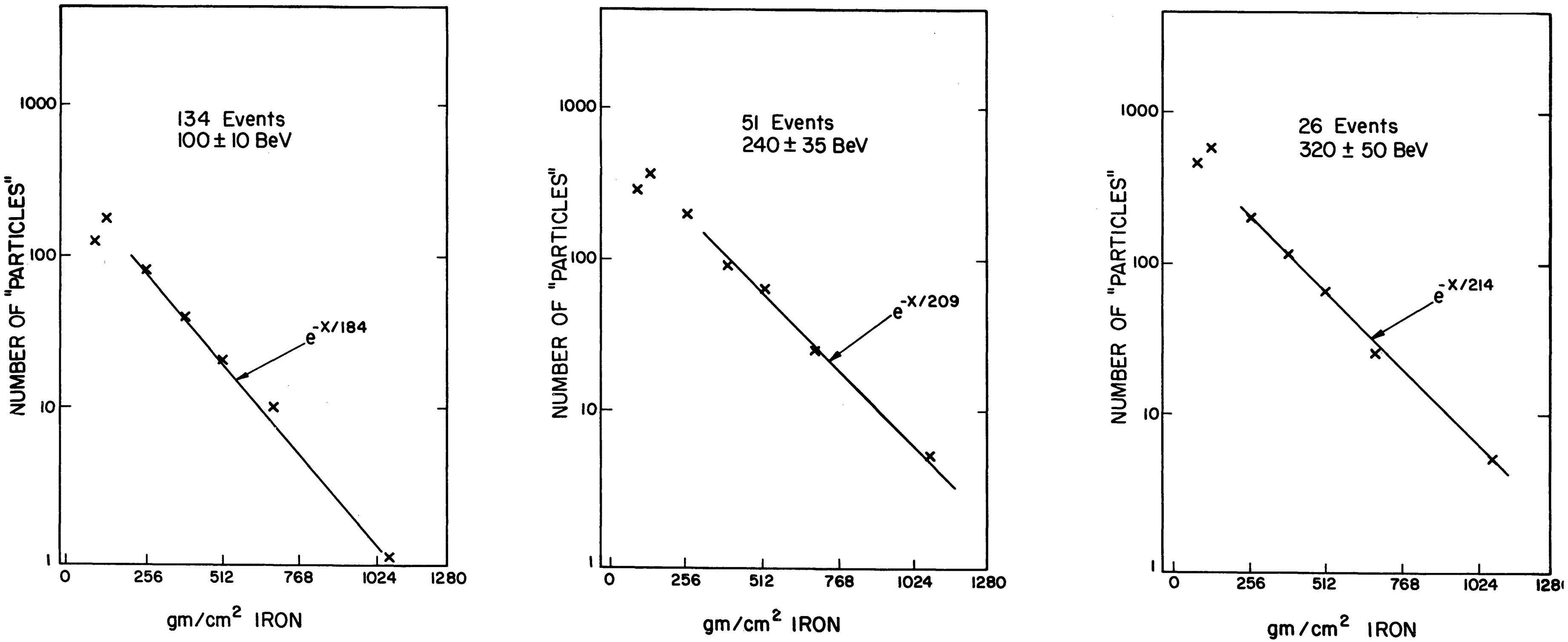
134 Events
100 ± 10 BeV
$e^{-X/184}$
51 Events
240 ± 35 BeV
$e^{-X/209}$
26 Events
320 ± 50 BeV
$e^{-X/214}$
NUMBER OF "PARTICLES"
1
10
100
1000
0
256
512
768
1024
1280
gm/cm^2 IRON

Figure 3

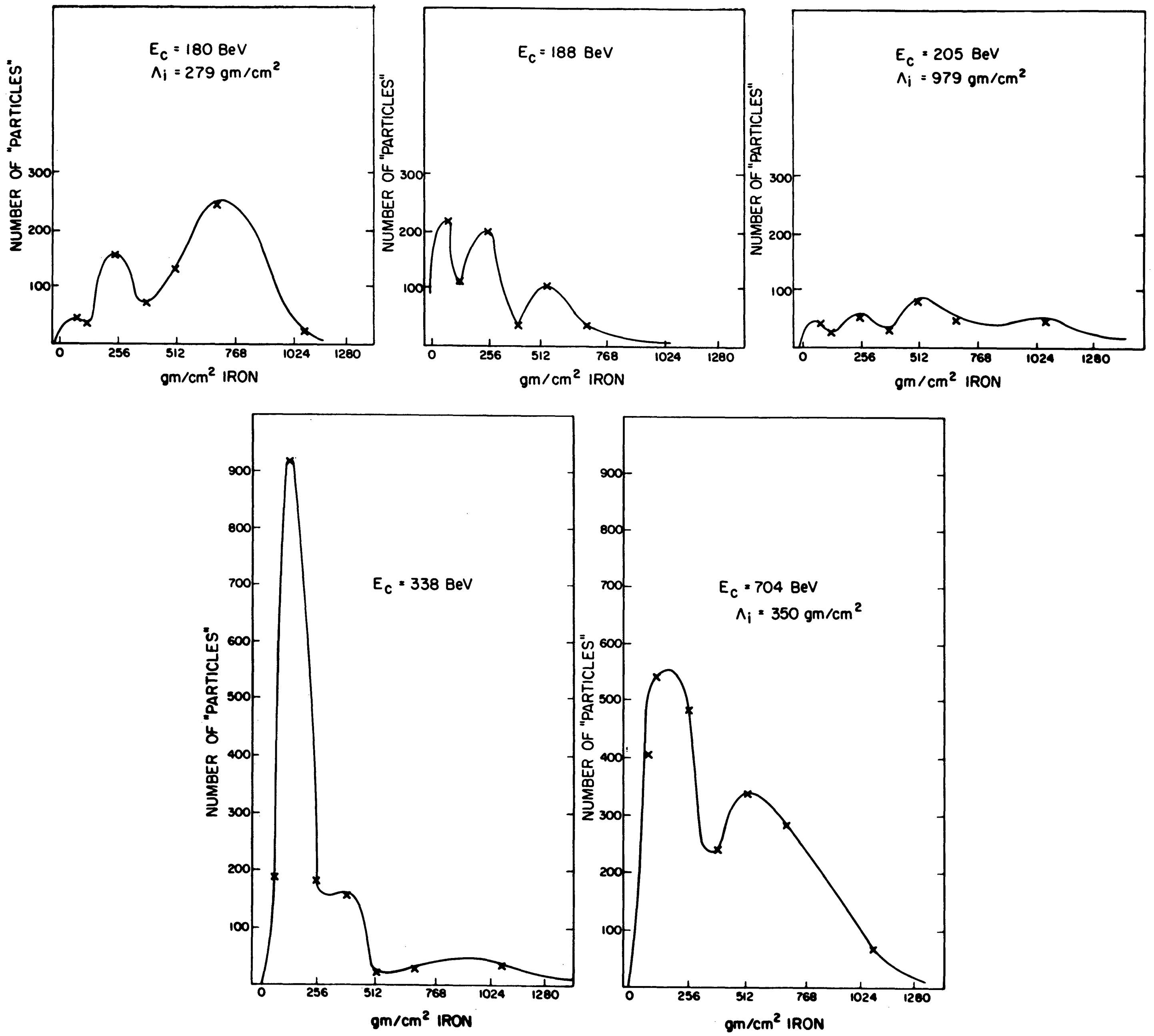
E_c = 180 BeV
Λ_i = 279 gm/cm^2
E_c = 188 BeV
E_c = 205 BeV
Λ_i = 979 gm/cm^2
E_c = 338 BeV
E_c = 704 BeV
Λ_i = 350 gm/cm^2
NUMBER OF "PARTICLES"
gm/cm^2 IRON
0
256
512
768
1024
1280
100
200
300
400
500
600
700
800
900

Figure 4

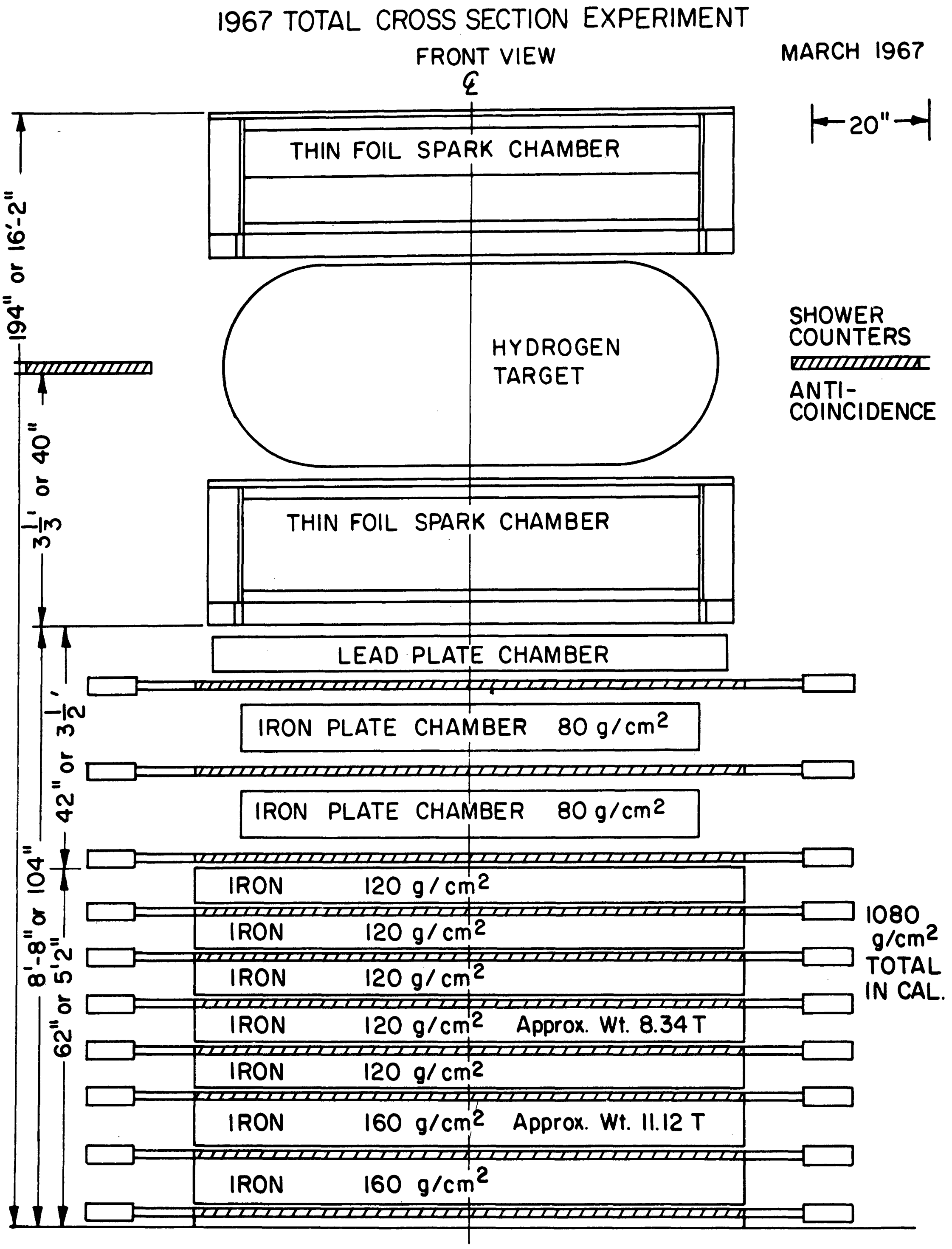
1967 TOTAL CROSS SECTION EXPERIMENT
FRONT VIEW
MARCH 1967
℄
20"
THIN FOIL SPARK CHAMBER
HYDROGEN
TARGET
SHOWER
COUNTERS
ANTI-
COINCIDENCE
THIN FOIL SPARK CHAMBER
LEAD PLATE CHAMBER
IRON PLATE CHAMBER 80 g/cm²
IRON PLATE CHAMBER 80 g/cm²
IRON 120 g/cm²
IRON 120 g/cm²
IRON 120 g/cm²
IRON 120 g/cm² Approx. Wt. 8.34 T
IRON 120 g/cm²
IRON 160 g/cm² Approx. Wt. 11.12 T
IRON 160 g/cm²
1080
g/cm²
TOTAL
IN CAL.
194" or 16'-2"
3 1/3' or 40"
3 1/2' or 42"
8'-8" or 104"
62" or 5'2"

Figure 5

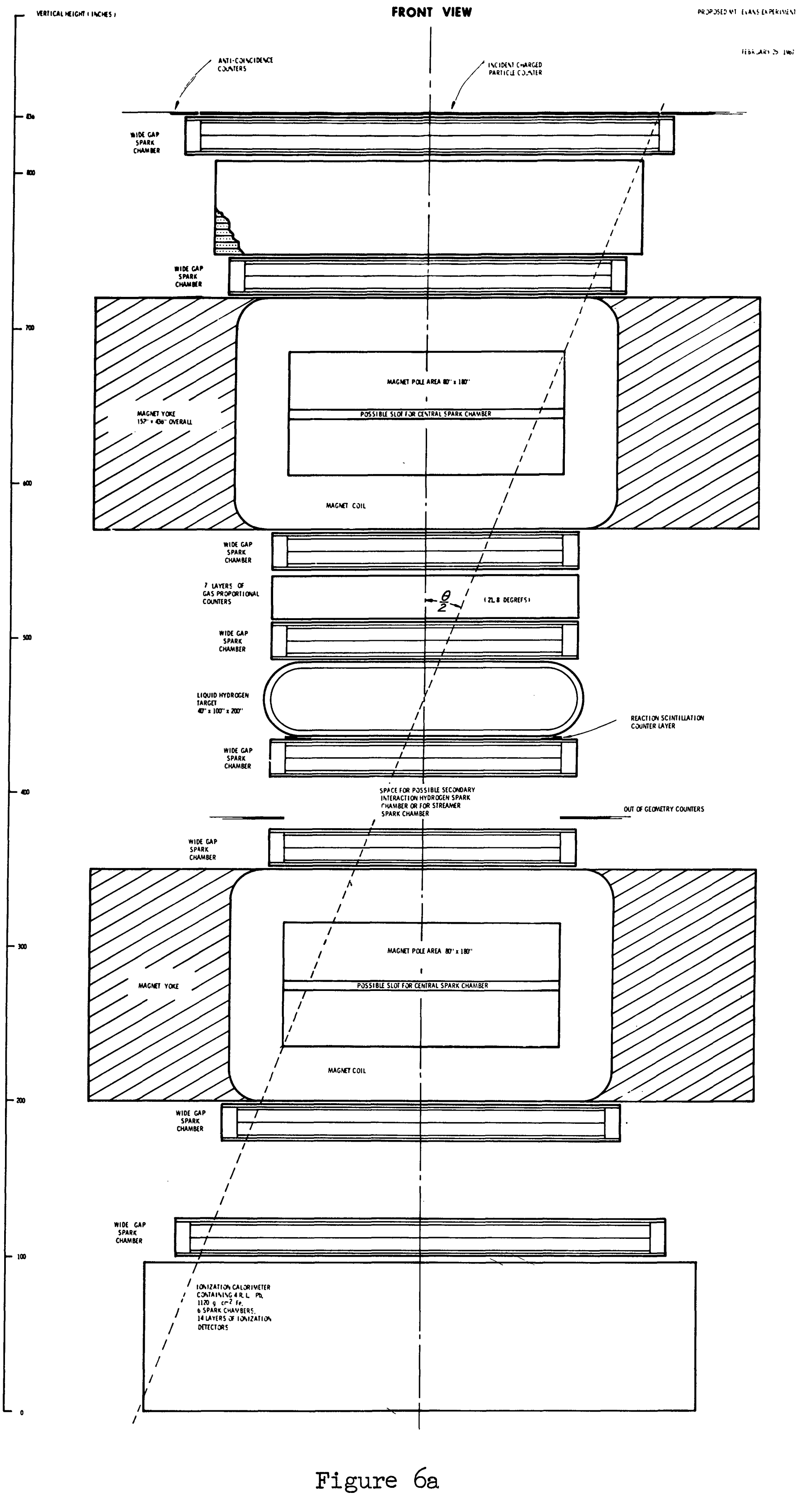
VERTICAL HEIGHT (INCHES)
FRONT VIEW
PROPOSED MT. EVANS EXPERIMENT
FEBRUARY 25 1967
ANTI-COINCIDENCE COUNTERS
INCIDENT CHARGED PARTICLE COUNTER
836
800
700
600
500
400
300
200
100
0
WIDE GAP SPARK CHAMBER
WIDE GAP SPARK CHAMBER
MAGNET YOKE 152" x 436" OVERALL
MAGNET POLE AREA 80" x 180"
POSSIBLE SLOT FOR CENTRAL SPARK CHAMBER
MAGNET COIL
WIDE GAP SPARK CHAMBER
7 LAYERS OF GAS PROPORTIONAL COUNTERS
$\frac{\theta}{2}$
(21.8 DEGREES)
WIDE GAP SPARK CHAMBER
LIQUID HYDROGEN TARGET 40" x 100" x 200"
REACTION SCINTILLATION COUNTER LAYER
WIDE GAP SPARK CHAMBER
SPACE FOR POSSIBLE SECONDARY INTERACTION HYDROGEN SPARK CHAMBER OR FOR STREAMER SPARK CHAMBER
OUT OF GEOMETRY COUNTERS
WIDE GAP SPARK CHAMBER
MAGNET YOKE
MAGNET POLE AREA 80" x 180"
POSSIBLE SLOT FOR CENTRAL SPARK CHAMBER
MAGNET COIL
WIDE GAP SPARK CHAMBER
WIDE GAP SPARK CHAMBER
IONIZATION CALORIMETER CONTAINING 4 R.L. Pb, 1120 g cm⁻² Fe, 6 SPARK CHAMBERS, 14 LAYERS OF IONIZATION DETECTORS

Figure 6a

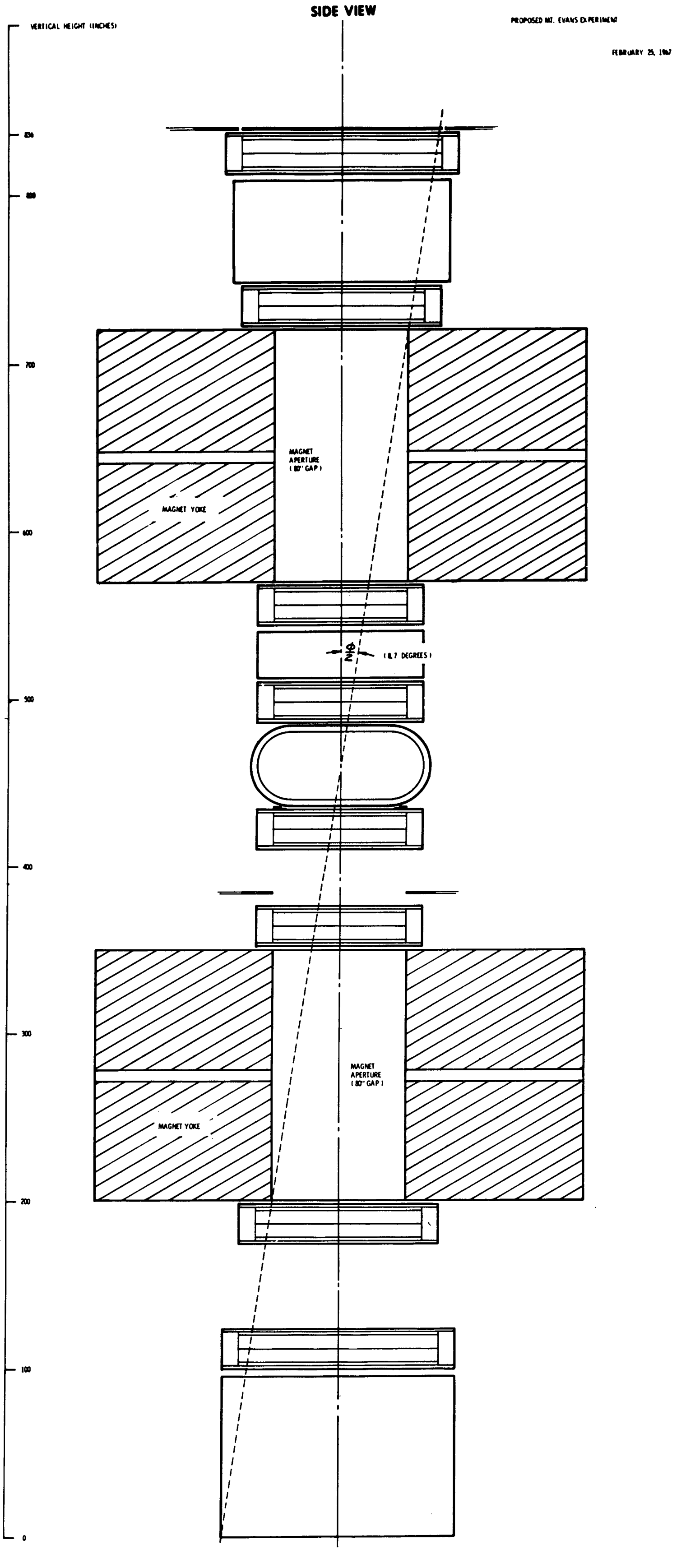SIDE VIEW
VERTICAL HEIGHT (INCHES)
PROPOSED MT. EVANS EXPERIMENT
FEBRUARY 25, 1967
836
800
700
600
500
400
300
200
100
0
MAGNET APERTURE (80" GAP)
MAGNET YOKE
$\frac{\Phi}{2}$
(8.7 DEGREES)
MAGNET APERTURE (80" GAP)
MAGNET YOKE

Figure 6b

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3. REPORT TITLE

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