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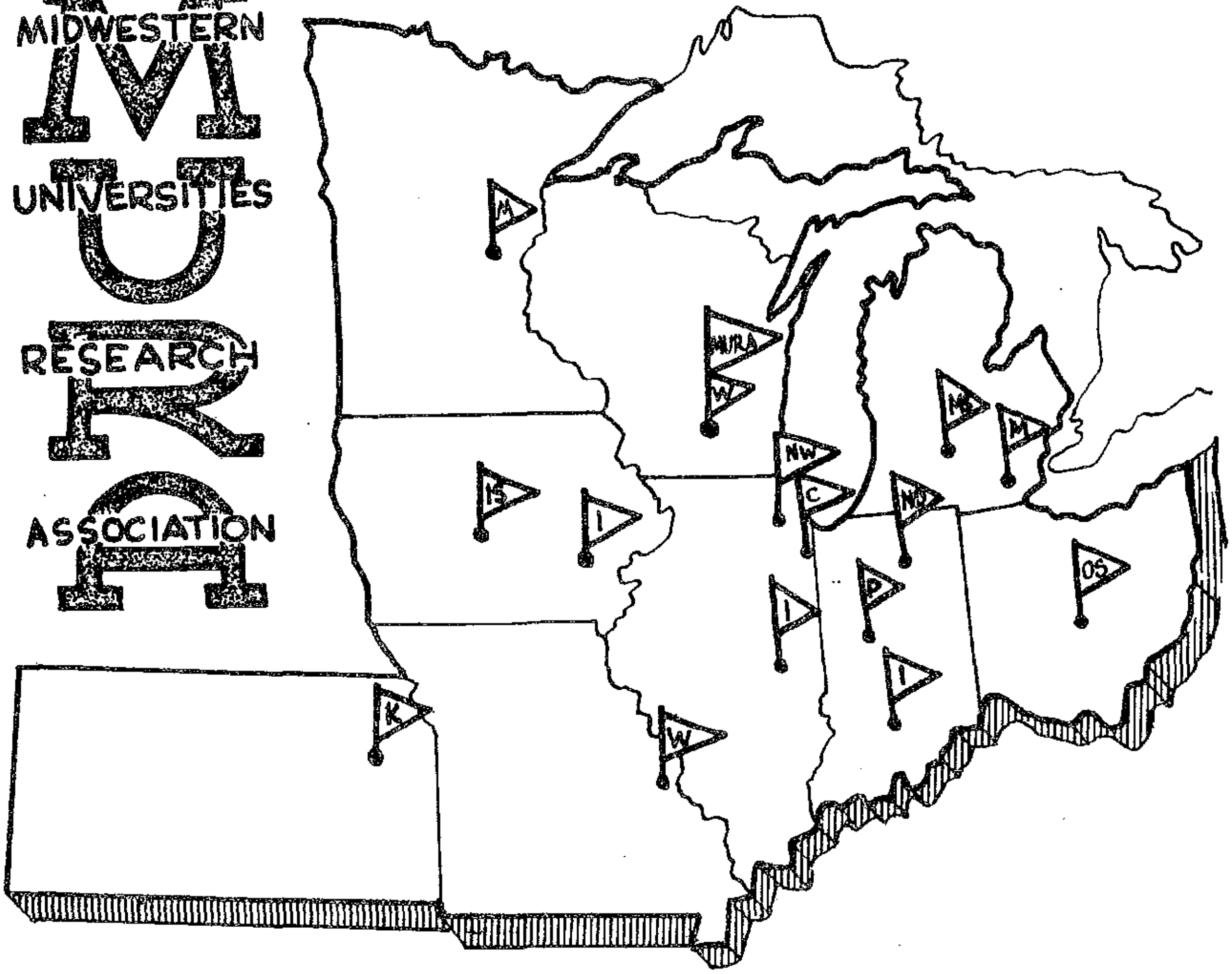

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ABSTRACT

A search for long-lived particles ($\gtrsim 10^{-6}$ sec) of mass in the range of about 5-15 BeV has been carried out among cosmic rays at the summit of Mt. Evans, Colorado, by measuring time intervals between the arrival of strongly interacting particles of energy $\gtrsim$ 70 GeV and accompanying air

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shower particles. From the absence of delayed strongly interacting particles in the range 40-180 ns where particles of nucleonic mass are not allowed, it is concluded that an upper limit of 160 μb/nucleon could be placed on the cross-section for production of particles of mass around 8 BeV at energies not far above threshold in nucleon-nucleon collisions. This limit is subject to certain restrictive assumptions about the behavior of the hypothetical massive particles, which are discussed.

I. INTRODUCTION

Possible existence of an elementary triplet of particles of mass much higher than that of a nucleon has been suggested by higher symmetry schemes of strongly interacting particles.[1] Search for massive particles[2] at the highest energies currently available at accelerators has indicated that if such particles exist, their masses are unlikely to be $\lesssim$ 5 BeV. It is of interest to look for the existence of particles of mass greater than about 5 BeV among secondaries produced by cosmic rays in the atmosphere. Accordingly a search has been conducted at Mt. Evans (14, 260 ft.), Colorado, for strongly interacting particles of mass $\sim$ 10 BeV and the negative result obtained in this experiment is reported here.

II. THE METHOD

The method adopted in this search is similar to the one suggested by G. Damgaard et al.[3] It consisted of measuring time delays between the incidence of "electrons" from high energy nuclear events in the atmosphere (air showers) and the arrival of strongly interacting particles of energy $\gtrsim$ 70 BeV.

If a particle of mass M and energy E is produced in a collision at a height Z above the level of observation, it will arrive delayed with respect to the accompanying soft component which travels essentially with the velocity of light c by

$$t = \frac{Z}{2\gamma^2 c} \;, \quad \gamma \gg 1 \qquad \text{-----} \quad (1)$$

where $\gamma = \frac{E}{M}$. The magnitude of time delays encountered is likely to be at least given by inserting in (1) Z = 1.1 km which corresponds to a nuclear collision mean free path at an atmospheric depth of $\simeq$ 600 gm/cm^2. This yields 37 ns, for example, for a particle of mass 10 BeV and energy 70 BeV. The corresponding delay for a nucleon of the same energy is 0.33 ns but maximum possible delay is given by using for Z the whole effective height of atmosphere above the level of observation. Taking $Z_{max} \simeq$ 14 km, nucleons can be delayed by as much as 4.2 ns. The likely distributions of time delays are discussed in Appendix (c). Thus, detection of particles heavier than nucleons is possible if delays above maximum possible values for nucleons of a given energy are obtained.

The method employed here imposes certain limitations on the properties of particles for them to be detected. These are: (a) they have to be long-lived, i.e. lifetime $\gtrsim 10^{-6}$ sec; (b) they should lose energy through nuclear interactions in passing through matter similar to that suffered by nucleons, and (c) the transverse momenta acquired by them in nuclear collisions should also be about the same as those acquired by nucleons. Condition (b) is necessary because of the method used to measure energies of strongly interacting particles by absorbing their energies in condensed material, as will be explained in Section III. Condition (c) is needed in order that appreciable probability of detecting both the strongly interacting particle and an accompanying air shower is realized.

An estimate of the frequency of detecting massive particles with the above properties is made in the Appendix and in Section IV. The advantage of the present method compared to other methods such as that of measuring masses of slow particles lies in the fact that large collecting areas, solid angles, and momentum bites are relatively easily achieved. In addition, no restriction on the magnitude of the charge of the particles is imposed.

III. THE EXPERIMENT

Fig. 1 is a sketch of the apparatus which was mounted inside a trailer. This setup was used in connection with another experiment on the flux of strongly interacting particles. It consisted of two spark chambers each of area 1.8 m x 1.5 m, spaced one above another by a layer of iron 110 gm/cm^2 thick. The strongly interacting particles were detected by three additional layers of iron and four layers of scintillators each covering an area of 0.55 m^2. The total amount of iron available for absorbing the energy of strongly interacting particles was 400 gm/cm^2 below the mean height of collision in the layer of iron between the spark chambers. The spark chambers were triggered by coincident signals in the four scintillation counter arrays of the absorption spectrometer which most often amounted to about 70 BeV for the energy of the incident strongly interacting particle. The energy estimates in individual cases are likely to be accurate to better than $\pm$ 50%.

Two large plastic scintillation counters (each of area 1.8 m x 1.8 m) were used to detect air showers accompanying the strongly interacting particles. The pulses from the spectrometer counters and the shower detectors were suitably delayed, displayed and photographed with a dual beam oscilloscope at writing speeds of either 40 or 100 ns/cm (Fig. 2). The response from the air shower detectors was adjusted such that the passage of even one particle through them exhibited a detectable pulse on the oscilloscope.

The data were gathered over a period of 130 hours of operation during the summer of 1965. In all, about 10,000 events were recorded but only about a quarter of these indicated an accompanying shower by the presence of pulse in both the air shower counters. Again, only half of these were useful in the sense that pulse locations could be read clearly.

IV. RESULTS AND DISCUSSION

The distribution of time intervals between the pulse T_1 (Fig. 2) from the bottom three layers of the spectrometer and the mean position of pulses (T_4 and T_5) from the two shower counters is given in Fig. 3. Only events with pulses from both the air shower counters were used for the study of delay distribution in order to reduce accidental background and jitter in the pulses from the large counters.

The significant result from Fig. 3 is the absence of events in which the accompanying shower precedes the strongly interacting particle by more than 40 ns. The distribution looks asymmetric but not in a physically significant sense. This asymmetry could be attributed to the geometrical disposition of the apparatus and systematic displacements in the reading of the start of large pulses from the spectrometer.

The width of the distribution in Fig. 3 is comparable to the width of the distribution due to transit time of light in the counter through multiple reflections. An idea of this distribution could be had from the dashed histogram in Fig. 3 which shows the distribution in arrival times of pulses due to passage of single particles through the counters arranged as shown in the inset.

The absence of events beyond 40 ns up to 180 ns (which is the upper limit in the present experiment) is difficult to relate in a straight forward way to an upper limit of production cross-section of massive particles in collisions of high energy nucleons with air nuclei. Many arbitrary assumptions will be involved but a rough estimate of the frequency of heavy particles relative to the flux of nucleons of energy $\gtrsim$ 70 BeV is deduced in Appendix (b) to serve as a guide line to general expectations here.[4] The upper limit to the observed frequency of events at 99% confidence level is arrived at from the estimate based on the analysis of the spark chamber pictures which indicate that during the period for which the sample for Fig. 3 has been accumulated, 4, 000 strongly interacting particles (nucleons) of energy $\gtrsim$ 70 BeV have been observed. The fact that no event with delay in the interval 40 - 180 ns has been observed is equivalent to 4. 6 potential events which have 1% chance of not being observed. Thus, the 99% confidence limit is $4.6/4000 = 1.2 \times 10^{-3}$. In Fig. 4 is drawn a curve connecting the upper limit to the production cross-section set by the observed confidence limit and the assumed mass of the heavy particles. It is to be remarked that this method of relating the observed frequency to production cross-section avoids the question of composition of events that go to make the sample in Fig. 3. Analysis of spark chamber pictures shows that about 60% of the events that exhibit association of pulses from both the air shower counters have a single strongly interacting particle with varying degrees of association of soft component of air showers, whereas 75% of all triggers are single strongly interacting particles with or without associated shower particles.

The upper limits we find here are very much higher than the cross-sections expected near threshold for production of massive particles which may reasonably be taken to be given by $\pi \left(\frac{\hbar}{Mc} \right)^2$. In the accompanying table is given the values of cross-sections expected i.e., $\left(M_{\pi}^2 \; / \; M^2 \right) \sigma_g$ where M_{π} is the mass of the pion and M the mass of the heavy particle and σ_g the inelastic nucleon-nucleon cross-section at high energies (30 mb). The corresponding frequency of detectable events in the present type of experiment at an elevation of 600 gm/cm^2 is given in the last column. Although cross-sections may be much larger at energies far above threshold, it is likely that contribution from these higher energy collisions to particles in the required range of time delays will be small.

Mass BeV	Cross-section in ub $(M_{\pi}^2/M^2)\,\sigma_g$	Expected Frequency of events relative to 10^5 nucleons of energy $\geq$ 70 BeV
5	24	8.8
7	12	7.9
10	6	2.7
14	3	0.4

Thus, there is need to push the upper limits obtained in this experiment down by at least two orders of magnitude. The accidental background in the present experiment arising from chance association of an air shower, the rate of which was found to be 80/sec, (two-fold coincidence rate of the shower counters kept side by side as in Fig. 1) with a strongly interacting particle in the time interval 40 - 180 ns is 1.1×10^{-5}.

Three other searches[5] have been carried out for massive particles using similar techniques. In all these experiments no positive evidence has been found suggesting the existence of massive particles.

V. CONCLUSIONS

It has been feasible to explore the possibility of production of long-lived ($\gtrsim 10^{-6}$ sec) particles of mass in the range 5-15 BeV in high energy nuclear collisions in the atmosphere. Maximum sensitivity of detection of these heavy particles is around a mass of 8 BeV in the present experiment. The upper limit to the cross-section for production of particles of mass around 8 BeV is 160 ub/nucleon provided these lose energy comparable to that of nucleons and acquire transverse momenta of the same order of magnitude as nucleons do in nuclear collisions. The expected cross-section for the production of these particles near threshold is ~ 10 μb/nucleon. Thus, there is need to collect more data to push the upper limits set here by at least two orders of magnitude. Figures for the upper limits and expected cross-sections for the masses in the range considered are given in Section IV of the paper. It appears not feasible to observe cross-section levels much below 10 μb/nucleon because of chance association between strongly interacting particles and air showers.

In the method adopted in this experiment, there is no restriction on the magnitude of charge carried by these particles. Restriction on the rapidity of energy loss could be removed by using a thick enough absorber in the spectrometer. However, the restriction on the transverse momentum is necessary for the observation of the associated air showers and is vital to the method.

VI. ACKNOWLEDGMENT

It gives us great pleasure to thank the members of the neutrino group of the Argonne National Laboratory, in particular Drs. T. Novey and R. Lundy for lending us the large scintillation counters and oscilloscope without which the present experiment would not have been possible. We should also thank Professor M. Perl for loaning us the scintillation counters used in the absorption spectrometer and Professor D. Meyer under whose supervision the spark chambers were constructed at the University of Michigan. Valuable engineering and technical assistance was provided,in particular, by W. R. Winter and J. Spooner from MURA, O. Haas and Billy W. Loo from the University of Michigan, and S. Smith of the Denver Research Institute; many other services which were provided by these institutions, too numerous to be mentioned here, contributed to the success of the experiment. Finally, we should thank Professor M. Iona for making our stay on the mountain comfortable.

APPENDIX

(a) Intensity distribution of heavy particles in the atmosphere

The intensity of strongly interacting particles in the atmosphere consist essentially of nucleons distributed as

$$N(E, X) = KE^{-(\epsilon + 1)} \exp(-X/\lambda_a) \qquad \text{-----} \quad (1)$$

where E is the energy, X is the depth in the atmosphere, K , a constant, $\epsilon \simeq 1.7$ and $\lambda_a = 120\ \text{gm/cm}^2$.

The source spectrum of heavy particles assumed to be created in pairs in nucleon-nucleon collisions can be written as

$$S(E, X) = \int_E^\infty N(E', X)\ W(E', E)\ dE'/\lambda_i \qquad \text{-----} \quad (2)$$

where $W(E', E)$ is the differential production spectrum of the heavy particles and λ_i is the nuclear collision (inelastic) mean free path of nucleons in the atmosphere. For the purpose of developing a simple model of production and detection of heavy particles, the differential production spectrum is assumed to be a δ - function:

$$W(E', E) = 2\ (\sigma_H/\sigma_i)\ \delta\ (E - M\ \sqrt{E'/2M_n}),\ \ E > E_{th} = M^2/M_n \qquad \text{-----} \quad (3)$$

Here σ_H is an energy independent cross-section for the production of heavy particles of mass M in pairs and σ_i the inelastic collision cross-section corresponding to λ_i; M_n denotes the mass of a nucleon.

Under the above conditions, for $E > E_{th}$

$$S(E, X) = (4K\sigma_H/\lambda_i\sigma_i)\,(2M_n/M^2)^{-\epsilon}\,E^{-(2\epsilon+1)}\exp(-X/\lambda a) \qquad \text{-----} \quad (4)$$

The intensity distribution of heavy particles can then be written as

$$H(E, X) = \int_0^X S(E, x)\exp(-(X-x)/\lambda a')\,dx \qquad \text{-----} \quad (5)$$

where $\lambda' a$ is the absorption mean free path of the heavy particles in air. Combining (4) and (5),

$$H(E, X) = (4K/\lambda_H)\,(2M_n/M^2)^{-\epsilon}\,E^{-(2\epsilon+1)}\exp(-X/\lambda' a)$$

$$\left[1 - \exp(-X/\lambda a + X/\lambda' a)\right]\,\lambda a\,\lambda a'/(\lambda a' - \lambda a) \qquad \text{-----} \quad (6)$$

where use has been made of $\lambda_H = \lambda_i\,\sigma_i/\sigma_H$. For $E > E_{th}$, $\lambda' a = \lambda i'/(1 - \alpha^{2\epsilon})$ where $\lambda i'$ is the collision mean free path in air of the heavy particles and α is the mean elasticity of the collision. Since we have little knowledge about $\lambda i'$ and α, we use $\lambda a' = \lambda a$ as a working hypothesis.[6] The distribution given by (6) then simplifies to

$$H(E, X) = 4K\,(2M_n/M^2)^{-\epsilon}\,E^{-(2\epsilon+1)}\,(X/\lambda_H)\exp(-X/\lambda a) \qquad \text{-----} \quad (7)$$

(b) Association with air showers

The efficiency of detection of an air shower associated with a strongly interacting particle depends on the area of the shower detector, its distance from the core of the air shower and the number and lateral distribution of particles in the shower. Before arriving at an estimate of the frequency of association of air shower with heavy particles, first such a frequency of association can be calculated for the case of nucleons detected at the level of observation (600 gm/cm^2) with our apparatus and compared with the observed frequency.

The model used for the calculation is to expand the intensity given by (1):

$$N(E, X) = N(E, O) \exp(-X/\lambda_i) \left[\sum_{o}^{\infty} (X/\lambda_i)^n \eta^{nE} / n' \right] \quad \text{-----} \quad (8)$$

and $\lambda_a = \lambda_i/(1 - \eta^{\epsilon})$. Values of $\lambda_a = 120$ gm/cm^2 $\lambda_i = 85$ gm/cm^2 and $\eta = 0.5$ are mutually consistent figures. Each term in the above expansion represents the number of collisions a high energy primary suffered in the atmosphere before degrading to the energy E. Thus, in each case history, the energy transferred to the shower is known for a given E. Assuming that the shower size at the level of observation is given by $N = Esh/2$ where Esh in BeV is the energy transferred to the air shower,[7] the efficiency of its detection can be computed for the apparatus used in the present experiment by requiring that at least one particle pass through each shower detector (area 3.35 m^2) located at a distance of 1 m and 3.4 m from the shower core. This efficiency is given by $\left[1-\exp(-S\Delta_1)\right] \times \left[1-\exp(-S\Delta_2)\right]$ where S is the area of each detector and Δ_1 and Δ_2 the average densities of the air shower at the two detectors, respectively.

Using the relation $\Delta(r) = Nf(r)/R_1^2$ where f(r) is the lateral distribution function for age parameter unity and R_1 the so-called characteristic scattering length,[8] the frequency of association with air showers for nucleons of energy > 70 BeV is calculated to be $\approx 30\%$ which agrees with that found in this experiment $\approx 25\%$.

In the case of heavy particle production, the production spectrum is taken to be given by (3) and the intensity of heavy particles given by (5) and (2) is expanded as

$$H(E,X) = (2/\lambda_H) \int_0^X \int_{E'=E_{th}}^{\infty} N(E',o)\,\delta\left(E-M\sqrt{\frac{E'}{2M_n}}\right) dE' \exp(-x/\lambda i)$$

$$\left.\sum_0^{\infty} (x/\lambda i)\,\eta^{n\epsilon}/n!\right] \exp(-(X-x)/\lambda' i) \sum_0^{\infty} \left((X-x)\alpha^{2\epsilon}/\lambda i'\right)^n/n! \qquad \text{----- (9)}$$

Each term in the above expansion after integration over x represents a case history of particles leading to the production of a pair of heavy particles and detection of one of them at a time. Using numerical values for η, α etc., it is possible to calculate the energy transferred to the air shower and the corresponding probability of detection the air showers with the given apparatus. In the present calculations the energy transferred from the heavy particles to the air showers is neglected; in this case, only η and λ_i are involved in the calculation.

For the purpose of comparing the experimental results with the calculations based on the model outlined above, the following ratio is evaluated:

$$R = \frac{\int_{E_{th}}^{\infty} H(E', X)\, \mu(E')\, dE'}{\int_{E_{ob}}^{\infty} N(E', X)\, dE'} \qquad \text{-----} \quad (10)$$

The numerator is the flux of heavy particles of energy larger than E_{th} and the denominator the flux of nucleons of energy larger than an observed threshold energy, E_{ob}, which in the present experiment is 70 BeV. $\mu(E')$ represents an efficiency factor for the detection of the heavy particles i. e., the accompanying air shower should be detected and the time interval between the shower front and the heavy particle should lie within the set interval in the experiment (40 - 180 ns). $\mu(E')$ is taken to be a product of these two efficiencies. In this section, the method of obtaining the efficiency of detection of the accompanying air shower was discussed. In the next the probability distribution of the time intervals is discussed.

(c) <u>The time delay distribution of heavy particles</u>

The distribution of time intervals between the arrival of the air shower front and the incidence of a heavy particle can be calculated to a first approximation by assuming that most of the contribution to the time lag comes from the last free path of traversal of the heavy particle in the atmosphere before it is detected. The problem reduces to a transformation of the integrand in (5) to a time lag distribution by using the relation

$$t = \text{time lag} = (Z_o/2\gamma^2 c)\ \ell n\,(X/x) \qquad \text{-----} \quad (11)$$

where $Z_o \simeq 7$ Km, is the "scale height" of the atmosphere, $\gamma = E/M$ and c the velocity of light. Assuming further that $\lambda'_a = \lambda'_i$, the time delay distribution is given by

$$\chi(E, X, t) = S(E, x)\ \exp\left(-(X - x)/\lambda'_i\right) \cdot \left|\frac{dx}{dt}\right|$$

$$= (4KX/\lambda_H t_o)\,(2M_n/M^2)^{-\epsilon}\, E^{-(2\epsilon + 1)} \times \qquad \text{-----} \quad (12)$$

$$\exp\left(-X \exp(-t/t_o)/\lambda a\right) \exp\left(-X(1 - \exp(-t/t_o))/\lambda'_i\right) \times$$
$$\exp(-t/t_o) \qquad \text{-----} \quad (13)$$

where $t_o = Z_o / 2\gamma^2 c$.

A simple approximation to the above distribution follows if we set $\lambda'_i = \lambda_a$; the distribution is then a pure exponential with a mean of t_o and this distribution is the one used to compute the efficiency of obtaining heavy particles within the set delay and, in turn, to calculate the ratio R to be compared with the experiment (section IV).

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4. Recently there have appeared calculations on the production of triplets and quarks by cosmic rays in the atmosphere based on various models. See R. K. Adair and N. J. Price, Phys. Rev. 142, 844 (1966) and G. Domokos and T. Fulton (Preprint from Johns Hopkins University).

5. G. Damgaard, P. Greider, K. H. Hansen, C. Iverson, E. Lohse, B. Peters and T. Rengarajan (Private Communication).

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Negative results have also been reported in searches specifically for fractionally charged particles in cosmic rays. See for e.g., A. W. Sunyar, A. Z. Schwarzschild, and P. I. Conners, Phys. Rev. 136, B1157 (1964) and D. A. DeLise and T. Bowen, Phys. Rev. 140, B458 (1965).

6. Any guess based on the properties of known strongly interacting particles regarding hypothetical super strong particles would be premature. Arguments based on near constancy of momentum transfers in nuclear collisions and mass of heavy particle might lead one to deduce $1 - \alpha \simeq 2\, q_\perp / M = .04$ for $q_\perp = 0.3$ BeV/c and $M = 10$ BeV. But λ_i' could be less than λ_i.

7. The relation between N and Esh is based on the estimate given by K. Greisen in Progress in Cosmic Rays Physics, Vol. III, Ed. by J. G. Wilson, North Holland, 1956, p. 130.

8. See for example W. Galbraith, Extensive Air Showers, Academic Press, 1958, p. 29.

CAPTIONS FOR FIGURES

Fig. 1 A drawing of the experimental arrangement

Fig. 2 Schematic drawing of the display of pulses on oscilloscope sweeps. T_1 to T_5 indicate the measured starting points of pulses numbered 1 to 5. During part of collection of data a sweep of 1 μ sec duration was used.

Fig. 3 Histogram of time intervals $(T_4 + T_5)\ 2 - T_1$ (see Fig. 2) shown by full line. The histogram drawn by broken line is the distribution of time intervals in the arrival of pulses from the shower detectors (1, 2) kept one above another as shown in the inset and responding to passage of single particles through them. The latter histogram is based on 472 events but has been drawn, normalized to 1302 events of the previous histogram for comparison. Events in which air showers precede the arrival of strongly interacting particles would appear on the negative side of the axis of time as shown here.

CAPTIONS FOR FIGURES (Cont'd.)

Fig. 4 A curve showing the sensitivity of the present experiment for the detection of particles of various masses. The curve relates the upper limit set for the cross-section per nucleon above threshold for the production of heavy particles in pairs in high energy nuclear collisions in the atmosphere and the mass of the particles thus created. The curve has been drawn by joining the four points shown which were obtained by calculations based on a model outlined in the Appendix.

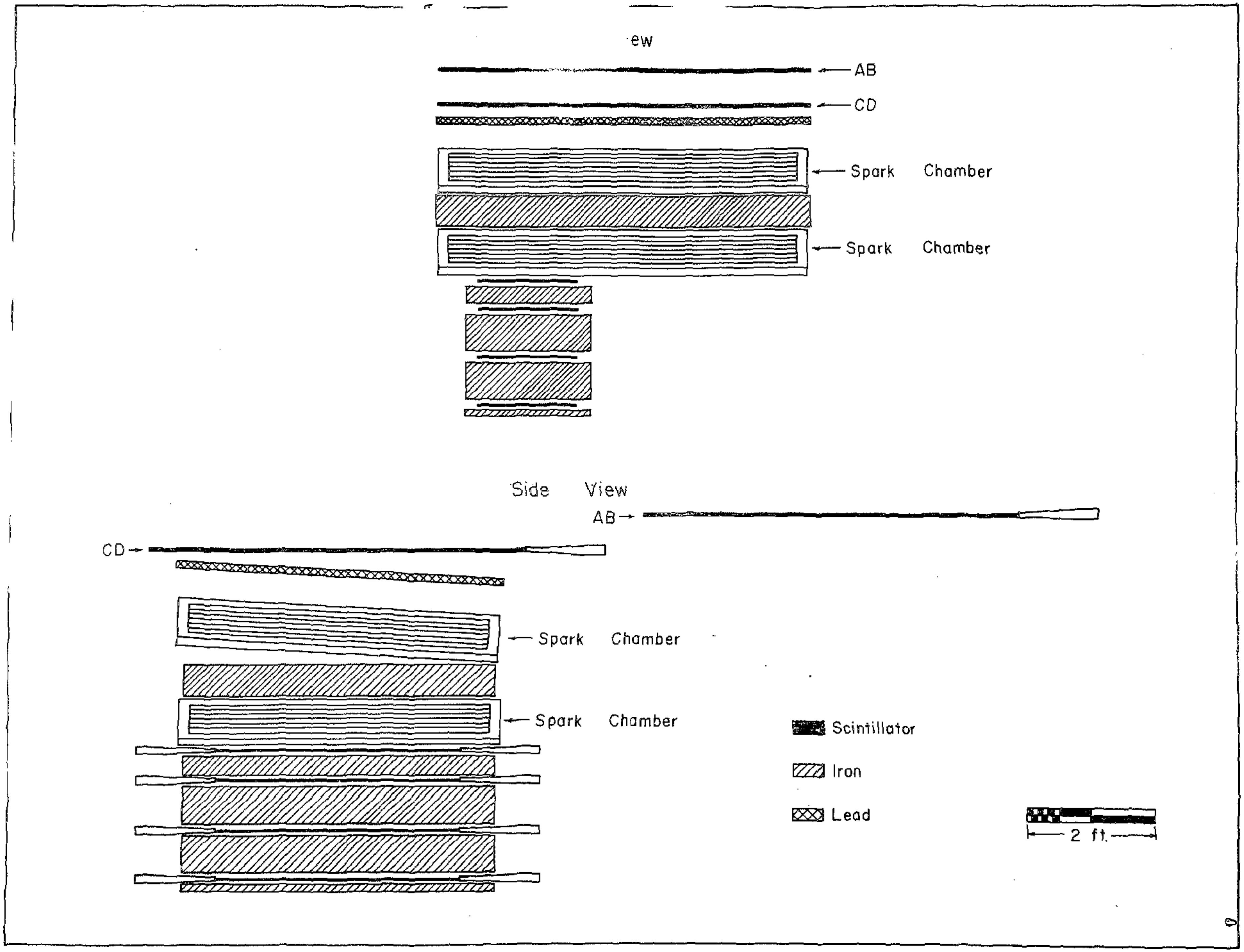
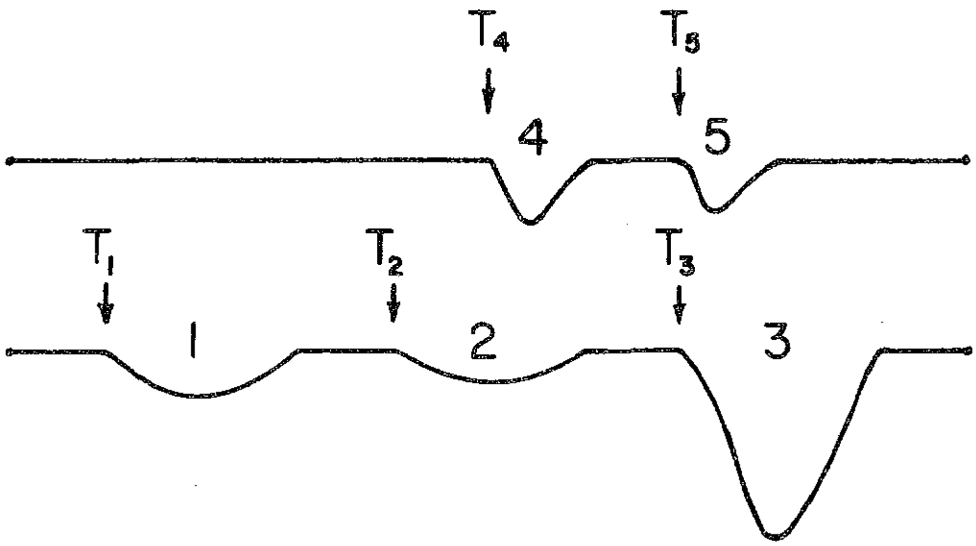

ew
AB
CD
Spark Chamber
Spark Chamber
Side View
AB
CD
Spark Chamber
Spark Chamber
Scintillator
Iron
Lead
2 ft.

Fig. I

Duration of sweep = 400 ns on 10 cm



1: Sum of pulses of lower three sections of spectrometer.

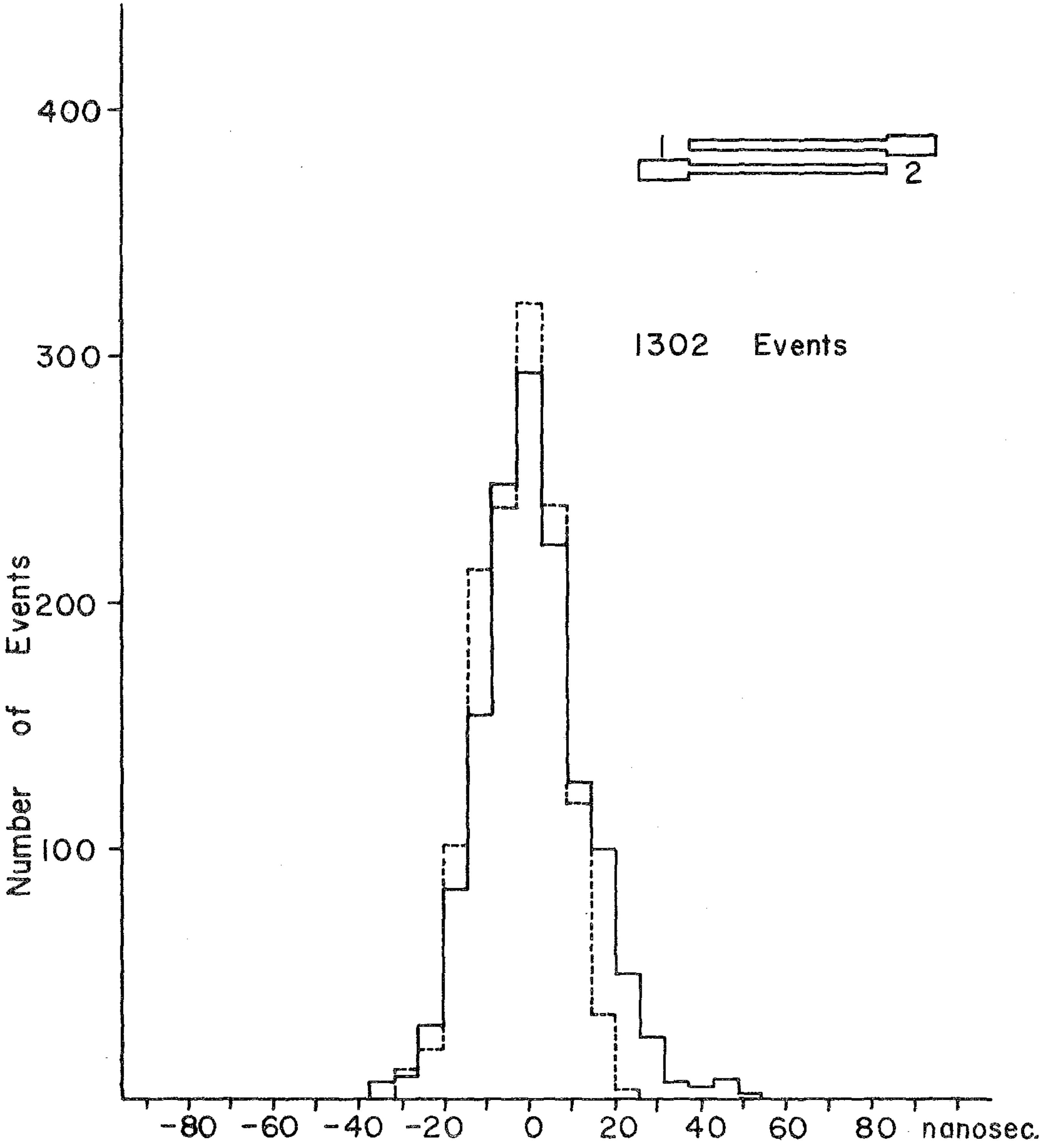
2: Pulse from top layer of spectrometer.

3: 2 amplified.

4: Pulse from counter CD on top of spectrometer.

5: Pulse from counter AB at the side of spectrometer.

Fig. 2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200
100
Number of Events
1
2
1302 Events
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Fig. 3

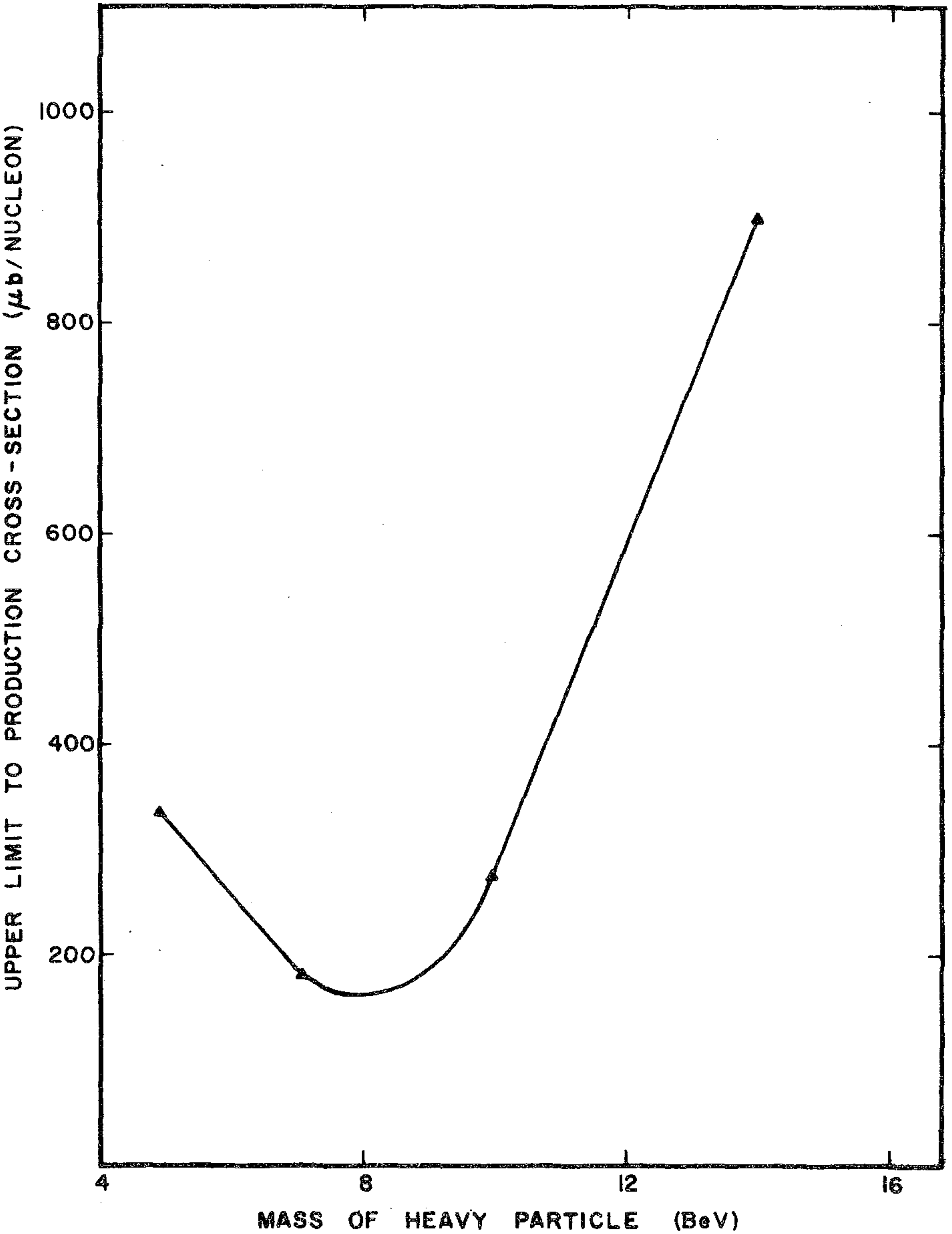
UPPER LIMIT TO PRODUCTION CROSS-SECTION (μb/NUCLEON)
1000
800
600
400
200
4
8
12
16
MASS OF HEAVY PARTICLE (BeV)

Fig. 4