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STATUS OF THE EXPERIMENTAL SEARCH FOR PHYSICAL QUARKS

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Up to the present time, there is no concrete evidence for the existence of physical quarks. I would like to summarize the experimental situation behind this statement with an emphasis on the model-dependent assumptions through which these experiments are interpreted as limits on quark mass and/or production mechanisms. I shall use the term "quark" throughout to refer to any new massive, stable hadron independent of charge. The searches for quarks fall into three discrete categories: accelerator experiments, cosmic ray searches, and studies of stable matter.

If quarks are to be produced in pairs, and each quark has a mass M, the threshold energy, E, for production of a quark pair in a proton-proton collision is

$$E/c^2 \cong 2(m+M)^2 / m \qquad (1)$$

where m is the nucleon mass, and the approximation is valid for $E >> mc^2$. Hence the threshold energy for making 10 GeV rest mass quarks is about 200 GeV, as an example. The cross section for producing quarks, if they exist, is highly speculative. Adair and Price[1] note that π, K, and $\overline{p}$ production are consistent with

$$\sigma_i \cong \pi a^2, \qquad a = \hbar/m_i c \qquad (2)$$

where m_i is the appropriate particle mass. If this also holds for quark production, cross sections would correspond to about a microbarn for 10 GeV rest mass quarks. The cross section would presumably rise to this value at two to four times the threshold laboratory energy. On the other hand Hagedorn[2] and Feinberg[3] have proposed various statistical or thermodynamic models of particle production at high energies which would give a production cross section falling exponentially with particle mass,

$$\sigma \propto \exp(-M/T) \tag{3}$$

where T is a hadronic matter "temperature" in collisions, typically taken as about 0.16 GeV. If this model has any validity (and it can be made to fit data on $\bar{p}$ and $\bar{d}$ as well as π and K production up to 30 GeV), even a 2.5 GeV quark would be produced only with a 10^{-35} cm^2 cross section and would not be seen in even accelerator experiments. Each additional GeV of quark mass would lower the cross section by 10^{-5}. While Hagedorn's model was able to fit older data, recently reported $\bar{d}$ production data from Serpukhov indicate yields of antideuterons significantly in excess of the Hagedorn prediction, so that this calculation may in fact be a pessimistic lower limit.

Accelerator searches for quarks are sensitive over the mass range accessible. For pair-produced quarks, this extends to 3 GeV for the Brookhaven A.G.S. Until recently, the most sensitive experiment[4] sets a limit corresponding to

$$d^2\sigma/(d\Omega dp) \leq 2\times10^{-36}\ cm^2 sr^{-1} (GeV/c)^{-1}$$

per nucleus for p of 9 and 10 GeV/c, corresponding to a nucleon-nucleon quark production $\sigma < 10^{-35}$ cm^2. The Fermi motion of the nucleons increases the effective threshold to 4 or 5 GeV mass for cross sections one or two orders of magnitude higher (reppectively). Other earlier accelerator limits are about two orders of magnitude poorer[5]. Two recent accelerator experiments have significantly lowered the cross section for possible quark production. At the CERN P.S. Allaby et al.[6] have set limits corresponding to $d^2\sigma/d\Omega dp \leq 7.2\times10^{-39}$ cm^{2}sr^{-1}(GeV/c)$^{-1}$ per nucleon for a charge of -1/3e, and $d^2\sigma/d\Omega dp \leq 5.2\times10^{-38}$ cm^{2}sr^{-1}(GeV/c)$^{-1}$ for a charge of -2/3 e (90% confidence level). The technique employed a beam channel tuned to momenta greater than the maximum beam momentum for integral charge and to 10.9 GeV/c for q = 1/3e. The proton beam energy of 27 GeV corresponds to a pair-produced quark threshold of 2.7 GeV without a Fermi momentum contribution. The cross section limit corresponding to the q = -1/3e limit above for isotropic quark pair production in NN reactions, $\sigma \leq 4.5\times10^{-40}$cm^2, lies below the Hagedorn calculation for quark masses of about 2.4 GeV and below.

The Serpukhov 70 GeV accelerator has recently been used to extend the limitation mass to 5 GeV[7]. For q = -2/3e, $d^2\sigma/d\Omega dp \leq 8\times10^{-36}$ cm^{2}sr^{-1}(GeV/c)$^{-1}$ per nucleon, or $\sigma < 4\times10^{-37}$ cm^2. The corresponding limit for q = -1/3e is $\sigma \leq 1\times10^{-35}$cm^2.

Another accelerator search, particularly relevant in view of Hagedorn's gloomy production cross section prediction, was carried out at SLAC[8]. Here electromagnetic pair production was studied, and limits set on mass and charge of possible unknown particles. The limits in this case depend upon only well-established electrodynamics. The mass upper limits set range from 0.2 GeV for 0.04e charge to 1.5 GeV for 0.7e charge (assuming the particle lifetime exceeds 10^{-7} sec).

In order to discuss the cosmic ray searches, it is first necessary to review the flux and energy spectrum of cosmic rays entering the earth's atmosphere. To an uncertainty of about a factor of two, the integral vertical proton flux in the earth's atmosphere can be represented by

$$N(E,y) = 1.5E^{-1.8} \exp(-y/\lambda_a) \qquad (4)$$

where N is the number of protons of energy greater than E GeV per $(cm^2 sr\ sec)$, y is the depth from the top of the atmosphere in gm cm^{-2} and λ_a is the attenuation mean free path of nucleons in air; 120 gm cm^{-2}. Thus at the top of the atmosphere the integral flux of cosmic ray protons of $E > 100$ GeV is about $4 \times 10^{-3} (cm^2 sr\ sec)^{-1}$ and this integral flux falls by about a factor of 10 for each factor of 3 in energy. At sea level the corresponding proton flux ($E > 100$ GeV) has fallen to $10^{-7} (cm^2 sr\ sec)^{-1}$. Cosmic ray production of quarks consequently would be dominated by events high in the atmosphere and would probably be produced at energies close to threshold. Adair and

Price[1] have calculated cosmic ray quark production vs. quark mass for an assumed one μb production cross section. Their result is reproduced in Fig. 1.

Cosmic ray searches for quarks have taken several forms. In the largest number of experiments, a large counter "telescope" has been built to search for relativistic particles of fractional charge (q of ±1/3e or ±2/3e) by measurement of ionization[9-15]. In order to minimize problems arising from Landau straggling of ionization loss, small pulses due to Compton electrons, and many other "dirt" effects, a large number (as many as 12) of independent ionization detectors or counters are used in each experiment. In addition, spark chambers or other track visualizing devices have been used to verify the acceptability of quark candidates. The experiments typically have a phase space admittance of 1/10 to 1 m^2sr and are operated for a period of months. From these many searches an upper limit to the quark flux is about $10^{-10}(cm^2 sr\ sec)^{-1}$. In Table I the results of some recent experiments are summarized. It has taken a very considerable effort to drive the limit from 10^{-9} to 10^{-10} $(cm^2 sr\ sec)^{-1}$. In view of the effort required and the negative results to date, I doubt if any group will soon push this limit another order of magnitude lower.

These searches are limited in their sensitivity by several factors. 1) Obviously they would not detect integrally-charged quarks. Neither would they normally detect charges greater than unit charge (e.g., q = 4/3e) should such states be the most stable form of quark "matter." 2) Quarks might only be produced in very high multiplicity reactions and might be accompanied (even at the earth's surface) by muons or electrons at lateral spacings of only tens of centimeters. These normal ionizing particles would then mask the quarks. 3) If quarks interact with nuclear matter in such a way that they are rapidly slowed down in the atmosphere through inelastic collisions, they might arrive at the earth's surface with $v \ll c$ and hence an ionization measurement would not be definitive. This is unlikely if quarks interact like other hadrons. Known strong interactions are characterized by an average four-momentum transfer of about 0.5 $(GeV/c)^2$. For a nucleon, this corresponds to an inelasticity (fraction of energy loss in a collision to incident energy) of about 50%. For a 10 GeV rest-mass quark, the same four-momentum transfer would correspond to less than a 10% inelasticity. Hence we would generally expect quarks to reach the earth's surface with a much greater fraction of the energy they had at production than the corresponding nucleons, even assuming the same interaction cross section.

A review of earlier accelerator and fractional charge cosmic ray quark searches is contained in a CERN report by Massam[16].

A second class of cosmic ray search has studied the momentum and velocity of energetic cosmic ray particles with a magnetic spectrometer and time-of-flight counters. Kasha and Stefanski[17] have set a flux upper limit of $2.4\times10^{-8}(\text{cm}^2\text{sr sec})^{-1}$ on particles of up to 300 GeV/c, corresponding to a 2 μb production cross section for particles of rest mass between 5 and 15 GeV (following the model of Adair and Price[1]). This experiment is of course also sensitive to quarks of integral charge. A somewhat similar search measured range and velocity of particles, seeking evidence for particles of $m > m_p$ and/or $|q| < |e|$, using range (in iron) and liquid threshold Cherenkov counters[18]. Two possible deuterons were detected corresponding to a flux of $1.3\times10^{-12}(\text{cm}^2\text{sr sec})^{-1}$, or an incident sea level flux of $4.8\times10^{-10}(\text{cm}^2\text{sr sec})^{-1}$, correcting for absorption in the apparatus. These figures may be regarded as effective upper limits to quark fluxes.

A third class of searches sensitive to quarks of integral or non-integral charge follows a method proposed by the Copenhagen group[19], and is illustrated in Fig. 2. If a cosmic ray proton produces a quark of 100 GeV with a rest mass of 10 GeV along with a number of other particles (pions, etc.) which give rise to a typical cosmic ray shower, a detector located some kilometers below the production event will observe the quark arrival delayed relative to the v = c shower particles by a readily measurable time interval. This interval is given by

$$t = y/2\gamma^2 c$$

where y is the distance between production and detectors and γ (assumed >>1) is the Lorentz factor of the quark. For

y = 2km and γ = 10, t = 33 ns. The experiments consist of an array of counters to detect showers and a separate detector for the quark (for example a stack of counters with absorbers between them for sampling the energy loss). Three experiments have been published[20,21,22]. The Copenhagen group[16] and our group[21] report essentially negative results. In our experiment[21] the quark detector was an ionization calorimeter: a scintillation-counter-absorber configuration capable of giving a rough (±20 or 30%) energy determination of any high energy hadron. One quark candidate was seen, although the probability is about 10% that it was a nucleon or otherwise spurious trigger. Because of the time delay technique, the limit to the quark flux depends on quark mass and on assumptions concerning the quark behavior in the atmosphere. The upper limit to the quark flux set in our experiment is given in Table II and Fig. 3. Also given is the quark production cross section upper limit for different assumed masses and for two extreme assumptions on quark interactions: 1) $\lambda_h = \lambda_a$ (quarks attenuated like nucleons in the atmosphere) and 2) $\lambda_h = \infty$ (quarks are totally unattenuated). The limit of $5\times10^{-10}(cm^2 sr\ sec)^{-1}$ is a somewhat poorer limit than set by fractional-charge telescopes. However the searches are complementary in that these time delay experiments are sensitive to integrally-charged quarks, and to quarks attenuated in the earth's atmosphere (our experiment was performed at 10,600 ft. elevation). These experiments must assume that quarks are produced with other particles and not at large transverse momentum with respect to the other secondaries (otherwise the shower particles would not arrive at the same laboratory as the quark).

The experiment of Dardo et al.[22] is somewhat of an enigma. They see a significant counting rate for delayed events in an underground detector. This would have shown up in our experiment[21] as a signal 100 times our upper limit. They suggest that the essential difference with our experiment is that our trigger was not sensitive to a "thin" or muon shower while theirs was, while in fact the trigger requirements were very similar. From my own personal bias and based on the experiment I know best, I am very skeptical of the results they report. Consequently I would assert that the class of time delay experiments gives no positive evidence for existence of physical quarks.

Finally, quarks have been sought in stable matter of the earth's crust. In order to relate the limit set here to the cosmic ray data a very brief ourder of magnitude estimate is useful. We may assume that the cosmic ray flux has rained on the earth at the present rate for 10^{10} years (3×10^{17} sec). Quarks produced by cosmic rays would mostly fall into the oceans and be mixed through sea water over this time. They would then be distributed through an average of about 2km (2×10^{5}g/cm^2) of matter. If the vertical quark flux produced by cosmic rays is φ(cm^{2}sr sec)$^{-1}$ there will be a dinsity of quarks in matter,

ρ, of

$$\rho = \frac{3\times10^{17}\pi\varphi}{2\times10^{5}} = 5\times10^{12}\varphi \; \frac{\text{quarks}}{\text{gm}}$$

or

$$\rho = 8\times10^{-12}\varphi \text{ quark/nucleon.}$$

A cosmic ray quark flux of $10^{-10}(\text{cm}^2\text{sr sec})^{-1}$ thus would correspond to a quark density in stable matter of about 10^{-21} quarks per nucleon. It is unnecessary to emphasize the speculative nature of this estimate; it is only useful orientation. The searches in stable matter involve mass spectrometric methods, magnetic levitation and Millikan oil drop experiments, and optical spectroscopy. The mass spectroscopic studies have set limits of 10^{-17}, 5×10^{-27} and 3×10^{-29} quarks per nucleon in iron meteorites, air, and sea water respectively[23]. These limits are strongly model dependent,(for example they depend strongly on the assumed concentration of quarks in samples through various means) and are generally regarded as optimistic.

A number of experiments were initiated during a period when some cosmologists predicted an inequality of proton and electron charge. These experiments were of course stimulated by the quark excitement. Basically, they are refinements of the Millikan oil drop experiment, wherein a non-integral charge is sought on oil droplets, graphite grains, or superconducting beads. In the latter two cases diamagnetic particles are suspended in a static magnetic field and their displacements studied in a horizontal electric field. Using the oil droplet technique, Rank has set limits of quark concentration of $<10^{-20}$ per nucleon[24]. Morpurgo has set limits of $<5\times10^{-19}$ per nucleon of graphite (he has seen no quarks in 2×10^{18} nucleons)[25]. Johnston and Franken, using superconducting niobium pellets, have set limits $<10^{-19}$ per nucleon[26].

In a series of spectroscopic experiments, Rank[24] has looked for the Lyman series hydrogen-like spectral lines of "quarkogen"; an electron bound to a +2/3 quark (or a -1/3 quark-proton nucleus). He has studied sea water, fresh water and possible biologically concentrated sources -- oysters, sea weed and plankton. The "quarkogen" is concentrated using electric fields over vaporized sources. The limits set by these experiments is $<10^{-18}$ quarks per nucleon.

In conclusion, I believe that it is fair to say that the excitements of quark hunting is dying away. I know of no new cosmic ray searches being initiated. Each new, higher-energy accelerator will surely mount a serious quark search, and I am sure that someone must be planning to look into moon dirt for stable quarks. At this time, I suspect that most experimentalists feel that physical quarks are either unobservable or do not exist.

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Table I

Cosmic ray limits on quark fluxes set by some experimental searches for particles of fractional charge. In almost all cases limits correspond to 90% confidence levels.

Group	Flux limit in particles per (cm^2 sr sec) $q = \pm \frac{1}{3}e$	$q = \pm \frac{2}{3}e$	$q = \pm \frac{4}{3}e$
Brookhaven Yale [a]	2.6×10^{-9}	2.0×10^{-9}	
Argonne[b]	4.5×10^{-10}	1.6×10^{-9}	
CERN[c]	4.5×10^{-10}	1.7×10^{-10}	1.6×10^{-8}
Cal Tech[d]	1.7×10^{-10}	2.0×10^{-9}	
Durham[e]	1.15×10^{-10}	8.0×10^{-11}	
Tokyo[f]	0.5×10^{-10}	7.5×10^{-10}	
Arizona[g]	$6.8\ 10^{-11}$	1.2×10^{-10}	

a Reference 9

b Reference 15

c Reference 11

d Reference 10

e Reference 12

f Reference 13

g Reference 14

Table II

Quark flux and production cross section upper limits for different assumed quark masses and for two assumptions on quark mean free paths, λ_h, in the atmosphere set by the experiment of Reference 17.

Quark Mass (GeV)	Quark production cross section upper limit (99% confidence level) in 10^{-30} cm^2 per nucleon	Quark flux upper limit (90% confidence level) in $(cm^2\ sr\ sec)^{-1}$
	$\lambda_h = \infty$	
5	0.10	3.2×10^{-9}
7	0.11	1.2×10^{-9}
10	0.16	5.0×10^{-10}
14	0.32	3.3×10^{-10}
20	1.57	4.5×10^{-10}
	$\lambda_h = 120\ gm\ cm^{-2}$	
5	1.8	8.8×10^{-10}
7	3.1	5.2×10^{-10}
10	8.3	4.0×10^{-10}
14	31.1	4.8×10^{-10}
20	263	1.2×10^{-9}

Figure Captions

Figure 1. Cosmic ray-produced flux of quarks at sea level with $p/Mc > 1$ for an asymptotic production cross section $\sigma = 10^{-30} cm^2$ as a function of quark mass. The flux is in units of particles per (cm^2 sr sec) (after Adair and Price[1]).

Figure 2. Time-delay method of searching for quarks as used in experiments of References 20, 21 and 22.

Figure 3. Upper limits (99% confidence level) to the cross section for the production of quarks (in pairs) in nucleon-nucleon cosmic ray collisions set by the results of the experiment of Reference 21. Curves are given for two assumed quark attenuation mean free paths; $\lambda_h = 120$ g cm^{-2} and $\lambda_h = \infty$.

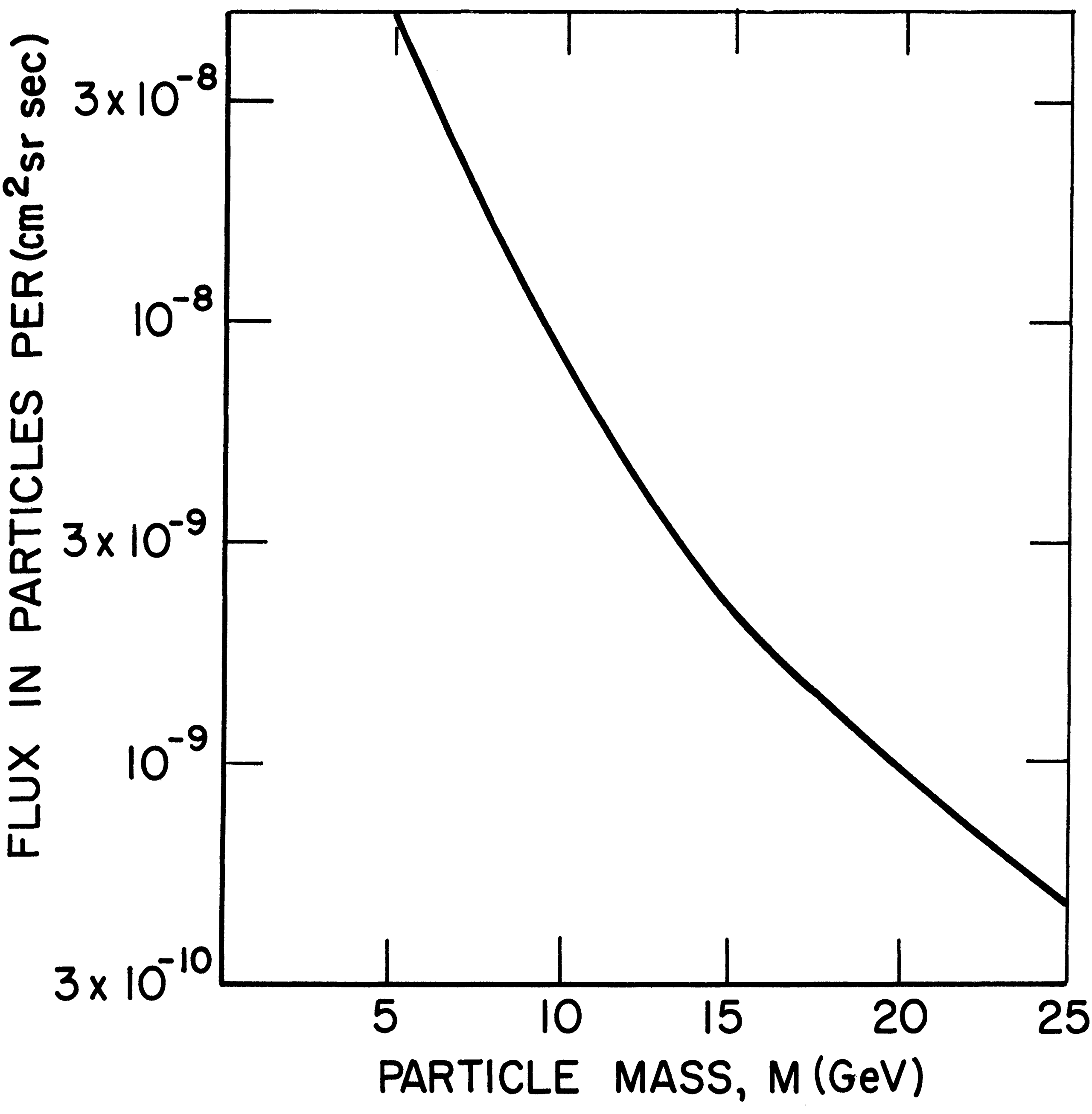
FLUX IN PARTICLES PER (cm2 sr sec)
3 x 10-8
10-8
3 x 10-9
10-9
3 x 10-10
5
10
15
20
25
PARTICLE MASS, M (GeV)

Fig. 1

SYSTEM FOR TIME DELAY DETECTION OF MASSIVE PARTICLES

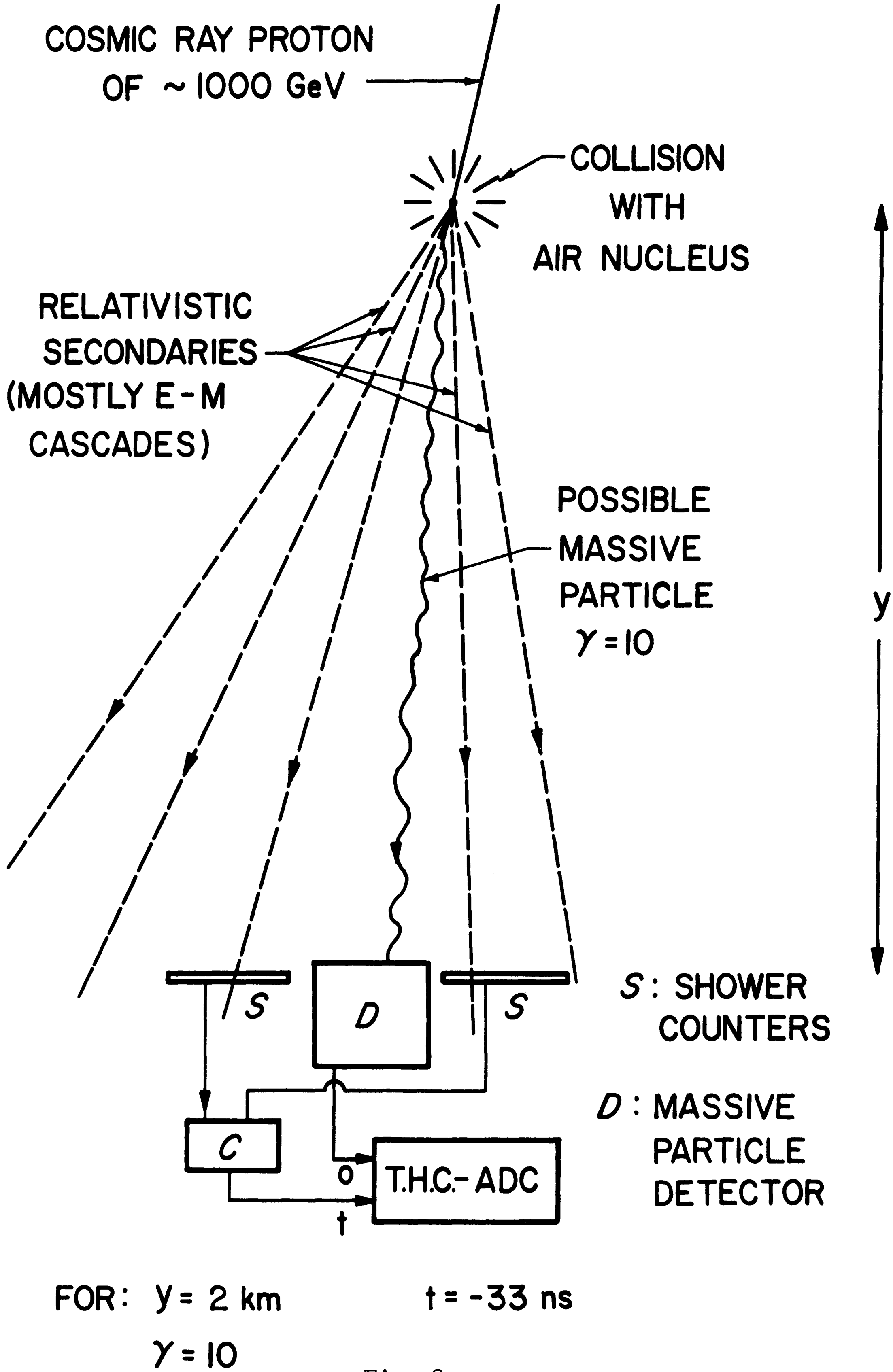

Fig. 2

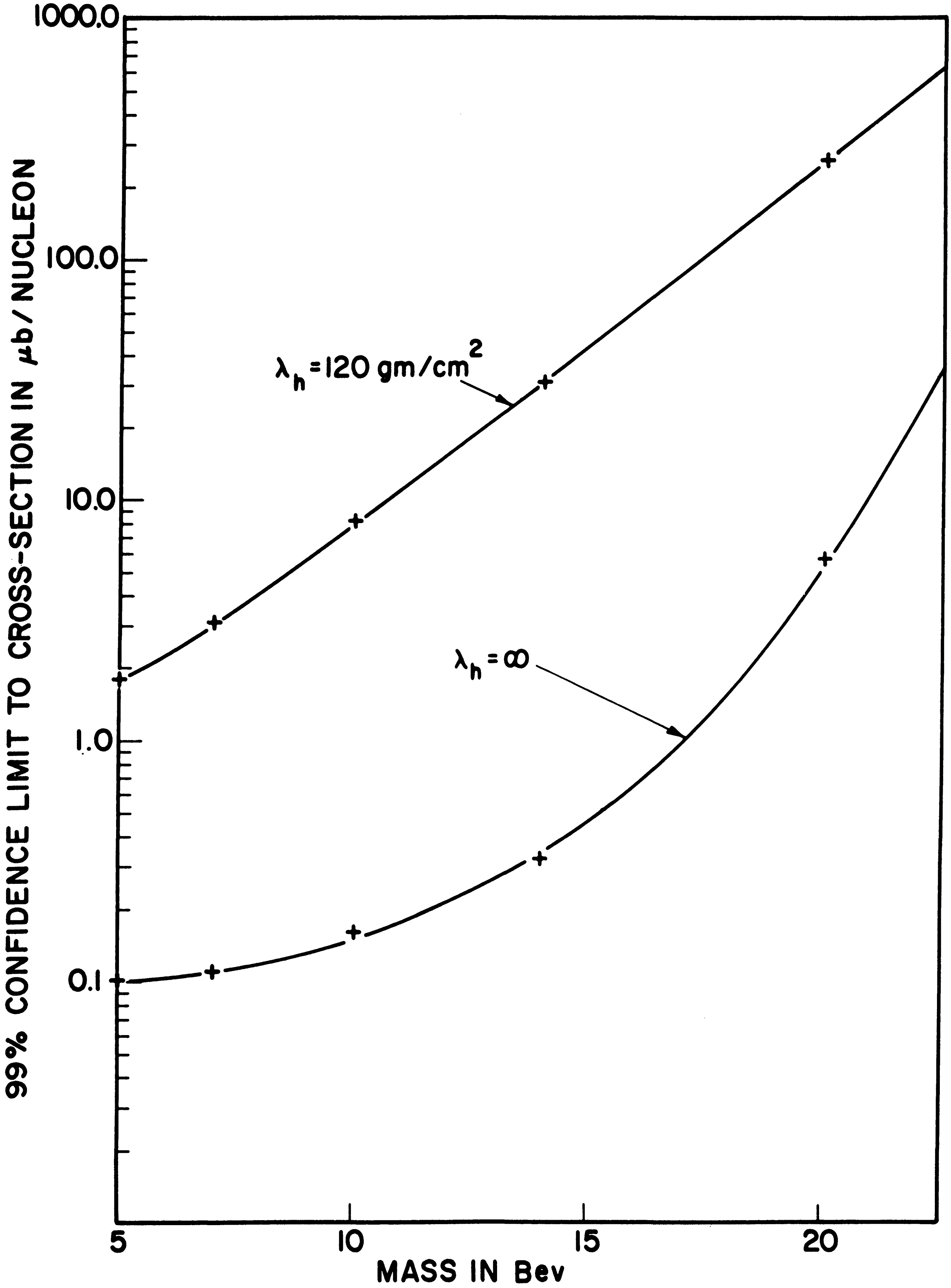
1000.0
100.0
10.0
1.0
0.1
99% CONFIDENCE LIMIT TO CROSS-SECTION IN μb/NUCLEON
λh = 120 gm/cm2
λh = ∞
5
10
15
20
MASS IN Bev

Fig. 3