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COSMIC RAY EXPERIMENTS
(Elementary Particle Physics)
IN A MANNED ORBITING LABORATORY

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ABSTRACT

Suggestions that the cosmic ray flux above the atmosphere would be a good source of ultra-high energy bombarding particles for high-energy experiments are discussed and evaluated. In view of current developments and anticipated improvements of man-made accelerators within the next decade, it is concluded that high-energy studies of this nature should not be programmed into a manned orbiting laboratory at this time.

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INTRODUCTION

There have been a number of suggestions that one use the high energy primary particles in the cosmic rays for experiments on high energy interactions to be performed in an orbiting laboratory. The cosmic rays were for a long time our only source of truly energetic particles, and most of the discoveries of new particles were made by using them. With the advent of more and more energetic accelerators, the use of cosmic rays as bombarding particles became less favorable because of their low intensity and the lack of control over the source. But it is still true that the only source of ultra-high energy particles is the cosmic ray flux on the Earth.

We first discuss the use of cosmic rays for high energy experiments and then described what can be achieved with accelerators that may be available within the next ten years.

HIGH ENERGY EXPERIMENTS WITH COSMIC RAYS

The integral spectrum of the primary cosmic rays at the "top" of the atmosphere (the number of particles with energy greater than E) is shown in Figure 1. The number of particles per sq. cm. per sterad per sec. is .15 for $E = 10^9$ eV, 10^{-5} for 2×10^{12} eV, and 10^{-19} eV for 10^{19} eV. Every second, two or three particles with energies greater than 10^{19} eV strike over the whole atmosphere of the Earth.

As the primary particles descend through the atmosphere, they are gradually attenuated and produce copious secondaries (with lower energies).

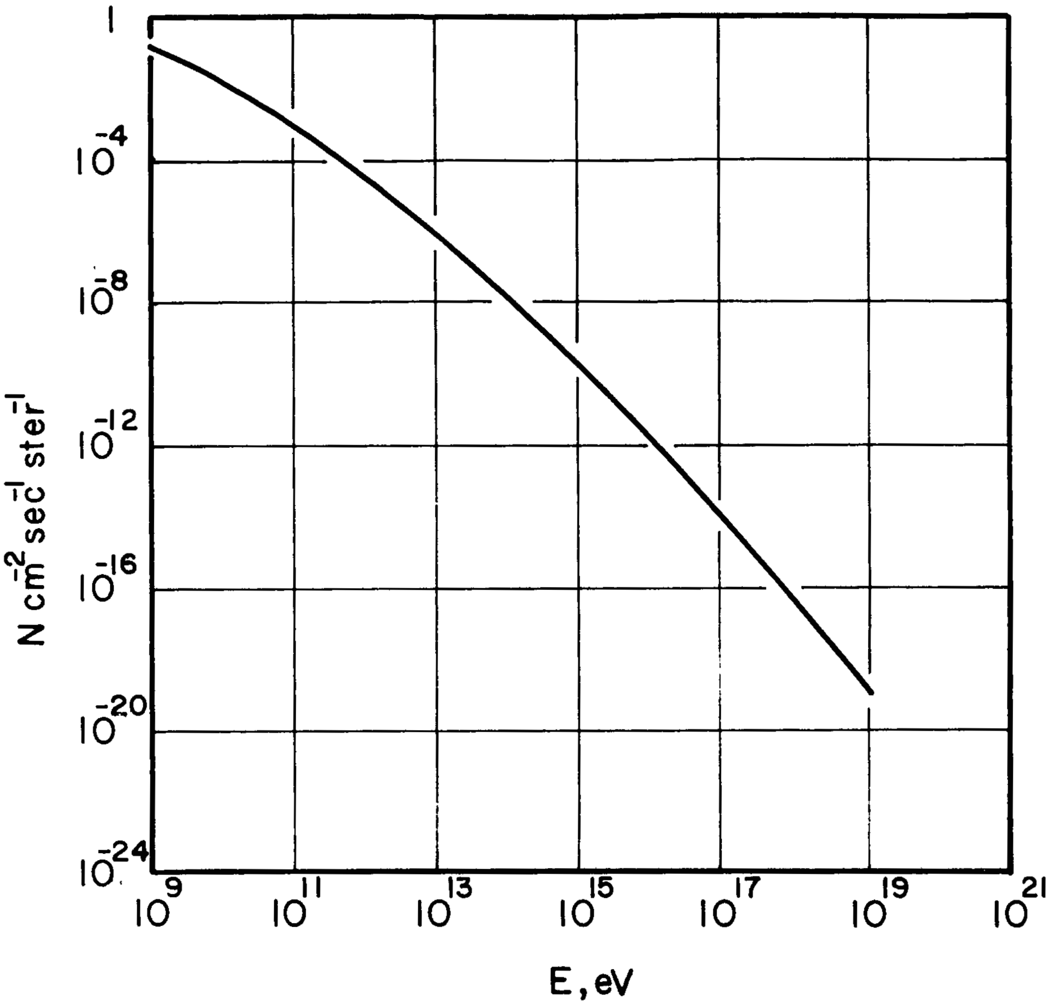

Fig. 1. Integral energy spectrum of primary cosmic rays.

These secondaries produced in the atmosphere by the entire spectrum of incident primary particles make it difficult to see the effects of the rare high-energy primaries. One obvious solution is to perform experiments with as little atmosphere as possible above the equipment. The atmospheric depth as a function of altitude above sea level is shown in Figure 2. The higher up one goes in the atmosphere, the less the attenuation of the primary beam and the less the background from secondaries. A laboratory is now being built on Mt. Evans for studying events produced by primaries with energies in the range 10^{10} - 10^{11} eV. For these a rough plot of vertical intensity with atmospheric depth is shown in Figure 3. Even the mountain height above sea level leaves about 60% of the atmosphere above the observer. The exponential in Figure 3 corresponds to an absorption length of ~ 120 g/cm^2 and shows that one would gain about 5 - 6 absorption lengths in going from Mt. Evans to a satellite "above" the atmosphere. The absorbers to be used in quark experiments on Mt. Evans will weigh $\sim 6 \times 10^4$ lbs. The equivalent experiments in a satellite would require only 100 - 300 lbs of absorber. Thus, experiments with reasonable loads of absorber could push the limits on the quark mass far beyond the present value. Experiments in an orbiting laboratory could also give valuable data on the fundamental (proton-proton) interactions above 1000 BeV.

HIGH ENERGY EXPERIMENTS WITH ACCELERATORS

Single Accelerators

At those energies that can be reached by accelerators, the accelerator is incomparably more effective as a source of bombarding particles than the cosmic radiation. Existing accelerators are operating at energies up to 30 BeV with fluxes $\sim 2 \times 10^{12}$ protons/sec. A target cross section of $\sim 10^{14}$ cm^2 would be required to give the same counting rate in a cosmic ray experiment in a satellite. The Russians have a machine under construction

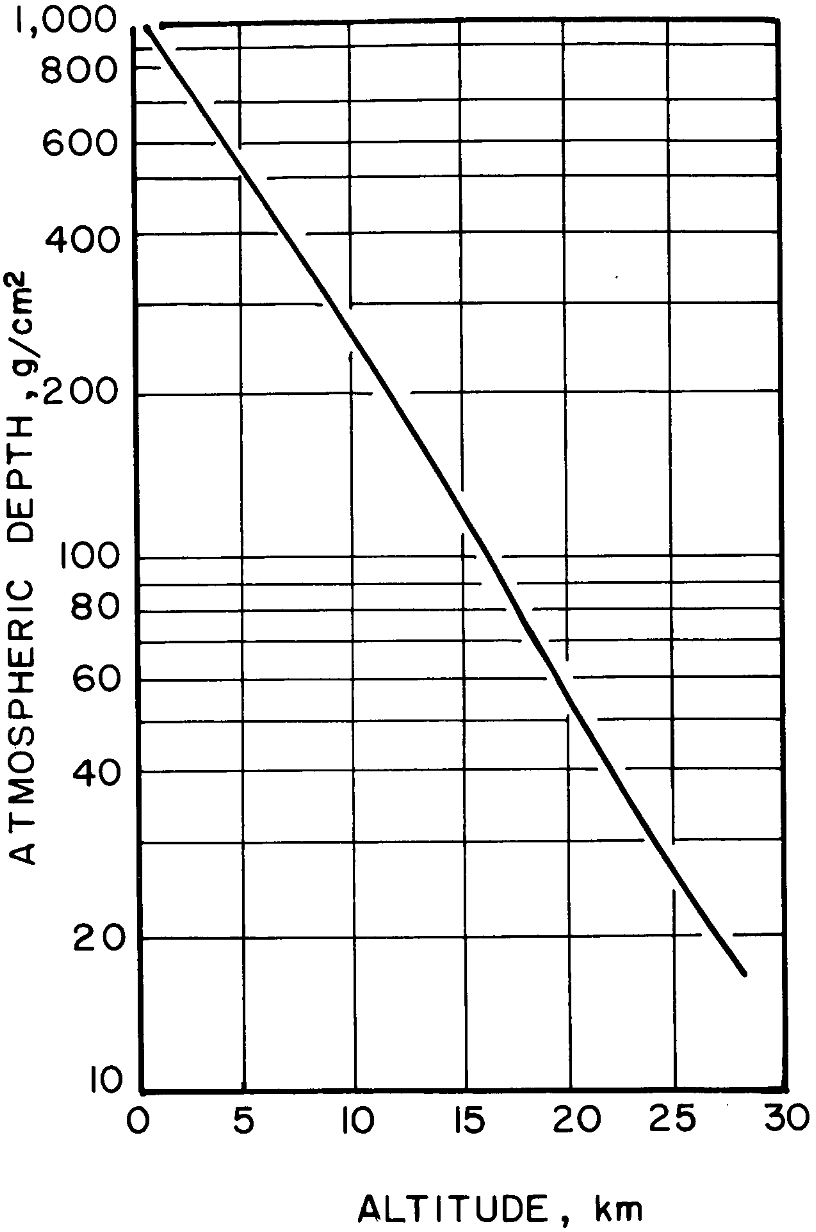

Fig. 2 Atmospheric Depth as a Function of Altitude above Sea Level.

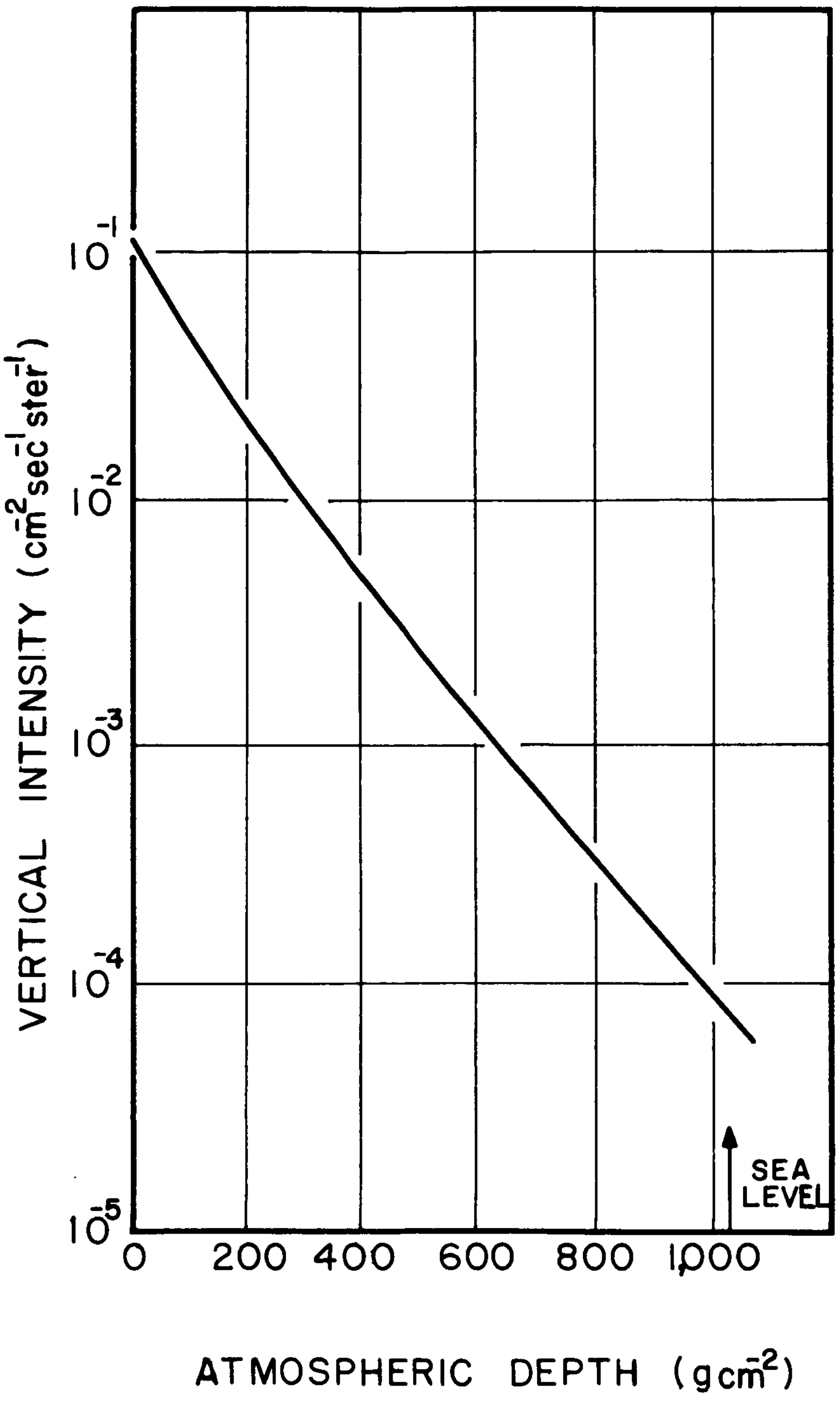

Fig. 3. Variation of Vertical Intensity with Altutude.

at 70 BeV and the U. S. is discussing a machine at 200 BeV.

Use of Colliding Beams

There is an ingenious procedure for extending the range of energies that can be reached by a given accelerator. In ordinary experiments a bombarding particle of high energy strikes a particle at rest. A large part of the energy of the bombarding particle represents energy of motion of the center of mass of the two particles. Only a fraction of the incident energy is available for the relative motion of the particles in their center-of-mass system (and it is this relative energy that determines how they interact with one another). On the other hand, if we fire two particles of equal mass at each other with equal speeds, their center of mass is at rest in the laboratory, and *all* of their energy is available for interaction. A rough formula relates the energy U of each of the colliding particles (equal masses M) to the energy U' of a bombarding beam giving the same center-of-mass energy:

$$U' \cdot Mc^2 \simeq 2U^2 \qquad (1)$$

For protons this simplifies to the rough form:

$$U' \simeq 2U^2 \qquad (U,\ U' \text{ in BeV}). \qquad (2)$$

Thus, two colliding beams with 10 BeV each are equivalent to a bombardment with 200 BeV particles, U = 20 gives U' = 800, U = 30 gives U' = 1800. This means that existing accelerators could already achieve the equivalent of 2000 BeV primaries by using colliding beams.

Offhand it appears that colliding beams would be very inefficient since the density of particles in a beam is found by dividing the flux (particles per sq cm per sec) by the velocity of light c, so that we lose a factor of 3×10^{10}.

From the figures in the preceding paragraph we see that this would leave only a factor of 3,000 in favor of the accelerator, and this could easily be balanced by using a 50 x 50 cm^2 target for experiments with cosmic rays. This conclusion would be correct if the colliding beams crossed once and then left each other. But we must remember that we are using cyclic systems in which the beam goes again and again around the same circular track. Thus, there are repeated chances for interaction at each revolution.

Two methods have been proposed for such colliding beam experiments. One method requires the use of two accelerators that are tangent along some straight section (Fig. 4a). The interactions occur in the overlap region. Since the particles are injected in pulses, one can further increase the interaction rate by bunching the particles.

Instead of using two accelerators, one can make use of a single accelerator and storage rings (Fig. 4b). These are annular magnets like those of the accelerator. Many pulses of particles from the accelerator are injected into each of the rings to fill them with a very high intensity circulating beam (amperes!) of protons. The two rings intersect at a small angle, and the interactions occur in the region of overlap.

Storage rings are being built for electron-electron collisons at the Stanford linear accelerator. CERN has carried on extensive design studies for devices to be used with their 25 BeV proton synchrotron.

The number of interactions per second, N_{int}, in a colliding beam machine is given by:

$$N_{\mathrm{int}} = \frac{c\,\tau\sigma}{h \tan \alpha/2} (N/L)^2 = c\,\tau\,\sigma\,(N/L)^2\ \ell/S \qquad (3)$$

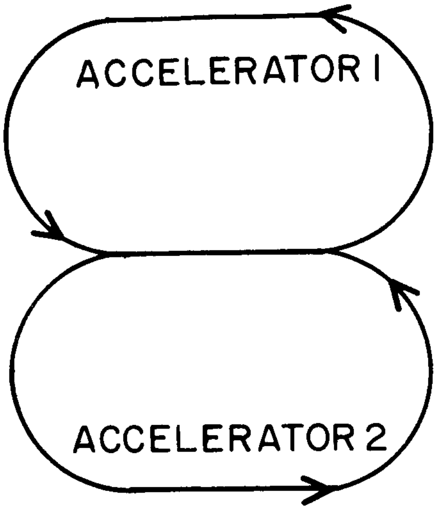

Fig. 4a. Tangent Accelerators

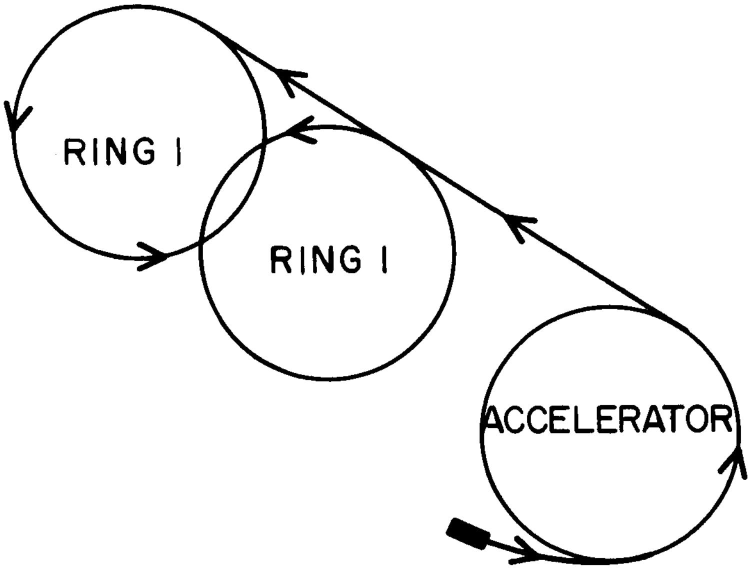

Fig. 4b. Storage Rings

for the case of storage rings, with

N = total number of circulating protons in each ring;
L = circumference of each ring;
h = vertical height of beam;
α = angle of intersection of beams;
S = cross section area of each beam;
τ = duty cycle (fraction of effective time)
ℓ = effective length of interaction region;
σ = proton-proton cross section ($\sim 40 \times 10^{-27}$ cm^2).

For tangent accelerators with bunching,

$$N_{int} = c\,\tau\,\sigma\,(N/L)^2\,\lambda/S, \tag{4}$$

where λ is the distance between bunches, and we assume that the length of a bunch is the interaction length ℓ. The CERN estimates, assuming that 5×10^{12} protons are injected per pulse, give $N_{int} \sim 10^3$ for storage rings and $\sim 10^4$ for tangent accelerators. With a cosmic ray flux of 10^{-5}/cm^2 sec, and assuming a nucleon density in the target of 6×10^{23}/cm^3, we would need a target volume of $\sim 10^{10}$ cm^3 to give the same counting rate in a cosmic ray experiment in a satellite.

CONCLUSION

It appears very likely that colliding beam experiments with protons will be available within ten years. We must, therefore, conclude that high energy studies in a satellite using cosmic ray primaries are not worthwhile, at least up to 2000 BeV. At higher energies we should note that the flux is falling so rapidly with energy that experiments would be practically impossible.

In conclusion we should emphasize that our comments apply only to the use of the satellite for high energy experiments. There are a variety of experiments on the cosmic rays themselves, their anisotropies and their spatial distribution (Van Allen belts) that should be done from satellites.