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HINTS OF NEW PHENOMENA AT VERY HIGH ENERGIES
FROM COSMIC RAY STUDIES

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HINTS OF NEW PHENOMENA AT VERY HIGH ENERGIES FROM COSMIC RAY STUDIES*

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The center-of-mass energies which will be achieved by colliding the main ring on the doubler have been crudely studied by cosmic ray work. For example, 150 on 1000 GeV is the equivalent of a $320 \text{ TeV} = 3.2 \times 10^{14} \text{ eV}$ incident proton on a stationary nucleon target. Several tantalizing effects have been seen in cosmic ray experiments above 100 TeV. Although the experiments are hard and the results may not always be properly interpreted, we should keep them in mind both to inspire us and to remind us to design flexible apparatus capable of observing the unexpected.

Hints from cosmic rays were reviewed by Bjorken¹ at the recent Fermilab Users Meeting and at the Very Big Accelerator (VBA) Meeting at Serpukhov. Halzen has also recently reviewed the implications of cosmic rays for new accelerators.² More extensive reviews are given by McCusker³ and Yodh.⁴

The two Centauro events seen in emulsion chambers on Mt. Chacaltaya by a Brazil-Japan collaboration are examples of a very unusual type of interaction.⁵ In the first event 90 ± 16 charged hadrons were observed, but $\sim 3\pi^0$'s! This number of charged tracks is much higher than the mean value of ~ 25 expected. The average transverse momentum of the individual particles, although not well determined, seems large, $\langle p_T \rangle = 1.7 \pm 0.7 \text{ GeV}/c$. The effective

*Contribution to the 1976 Fermilab Summer Study of the Doubler as Collider. Work supported by the U.S. Energy Research and Development Administration.

mass of the group of charged particles was estimated to be 210 ± 60 GeV and the energy of the incident particle to be about 2000 TeV. The second event was very similar, except that the visible energy was found to be 282 TeV, in the range of interest for main ring on doubler. It seems quite unlikely that these events are simply fluctuations of normal hadronic interactions. There are also several arguments against these events being the dissociation of very heavy nuclei into individual nucleons:

1) the transverse momenta are large; 2) there is a considerable energy spread (1 to 16 TeV) in the products, whereas the break up of heavy primaries leads to almost mono-energetic products; and 3) the interaction mean free path of very heavy primaries is short and the depth in the atmosphere at which the events were observed corresponds to 14 collision lengths.

Another event with very high multiplicity was observed several years ago by a Bristol-Tata Institute collaboration.⁶ Known as the Texas Lone Star event, it had both charged particles and γ rays, about 400 pions out of a total of about 500 created particles. The incident energy was estimated to be about 10^6 GeV. As has been found in several different observations at very high energies, the average transverse momentum of the particles was considerably higher than at present machine energies, in this case 700 MeV/c.

The Brazil-Japan collaboration also observed events with high γ -ray multiplicity at high energies and large effective masses (~ 5 GeV) of the γ ray bundles. For $\{E_\gamma \gtrsim 20$ TeV, $N_\gamma \gtrsim 40$.

These so called SH events tend to have higher transverse momenta of the secondaries than do the lower energy events.

In addition to having specific events with many γ rays, or with high multiplicity but very few γ rays, there are also measurements of the charged to neutral ratio of hadrons in extensive air showers that suggest a threshold for new phenomena in the few hundred TeV region. For incident energies of ~ 240 TeV, Vatcha and Sreekantan⁷ reported values of $c/n \sim 2$ for hadrons of ~ 100 GeV, whereas Gaisser and Rudolf⁸ have shown that on the basis of extrapolating lower energy data on the production of $n, \bar{n}$ and K^0 's, one would expect only a small neutral component and a value $c/n \sim 10$. Measurements by Ashton et al.⁹ at lower energies (100-200 TeV) show $c/n = 9 \pm 2$ for hadrons with $E > 25$ GeV, in good agreement with the calculations. If the higher energy experiment is correct, it indicates the onset of a new phenomenon such as a large increase in $N\bar{N}$ production or the production of a new kind of stable neutral particle.

A curious effect was observed in the Tien Shan calorimeter.¹⁰ Looking at the distribution of energy as a function of depth in the calorimeter, they observe a variation with incident energy of attenuation length deep in the calorimeter, as shown in Fig. 1. In particular, they observe a step in the attenuation length near 100 TeV, from 686 ± 25 to 1100 ± 100 g/cm². This might suggest the production of new hadrons with a small inelastic cross section (quarks??).

There have also been suggestions of massive particles. Air showers contain particles with almost all having velocities very

close to c and the particles normally arrive all within 7 nsec. In a Tata experiment¹¹ looking at high energy showers (~ 200 to 5000 TeV), energetic particles were observed >28 nsec behind the shower front. Using a cloud chamber to reduce the possibility of chance coincidences, they observed two late particles, each with about 30 GeV energy. Alcock et al.¹² observed two anomalous events in a range-velocity telescope. Comparing the time of flight and dE/dx measurements they estimate 90% confidence limits on the masses of (4.2 to 38) GeV and >8.5 GeV. A peculiar 3-prong event was observed in a large cloud chamber by a group from the Yunnan Institute.¹³ Two of the tracks had normal ionization, but the third track, with momentum greater than the maximum detectable momentum of 48 GeV/c, had a dE/dx indicating a mass >12 GeV.

Since the cosmic ray flux is falling rapidly at these high energies, the phenomena studied are not rare, but must have sizable cross sections. This bodes well for the main ring colliding with the doubler, which will have high center of mass energy, but will no doubt start with a low luminosity. The cosmic ray studies suggest that various completely novel phenomena may have a threshold in the neighborhood of 100 TeV and we should keep an open mind when designing and analyzing experiments at these energies. Even such "mundane" parameters as multiplicity may well turn out to be of great interest.

1. J. D. Bjorken, "Physics Issues and the VBA", contribution to the Very Big Accelerator Meeting, Serpukhov (May, 1976).
2. Francis Halzen, "Hadron Collisions above 10 TeV or Guessing Particle Physics at New Accelerators", talk at the Multi-Particle Colloquium, Tutzing, Germany (June, 1976), C00-560.
3. C. B. A. McCusker, Phys. Reports 20, 229 (1975).
4. G. B. Yodh, Rapporteur Talk at the Munich Cosmic Ray Conf. (Aug, 1975).
5. Brazil-Japan Emulsion Chamber Collab., Proc. Hobart Conf. on Cosmic Radiation, 2773 (1971); CKJ Report 13; and Munich Cosmic Ray Conf. (Aug. 1975).
6. P. H. Fowler and D. H. Perkins, Proc. Roy. Soc. A278, 401 (1964).
7. R. H. Vatcha and B. V. Sreekantan, J. Phys. A6, 1050, 1067 and 1078 (1973).
8. T. K. Gaisser and Paul Rudolf, "Neutral Hadrons in EAS: An Energy Threshold above 10^5 GeV?", Franklin Institute preprint (1976).
9. F. Ashton et al., Munich Cosmic Ray Conf. 8, 2980 (1975).
10. V. I. Yakovlev et al., Munich Cosmic Ray Conf. (Aug. 1975).
11. S. C. Tonwar et al., J. Phys. A5, 569 (1972).
12. C. R. Alcock et al., Denver Conf. on Cosmic Radiation 3, 2106 (1973).
13. Cosmic Ray Research Group of the Yunnan Inst. of Atomic Energy, Scientia Sinica XVI, 123 (1972).

Figure 1 : Energy dependence of the penetration depth of hadrons or shower cores through lead as a function of their energy.