CAN COSMIC RAYS REPLACE ACCELERATORS?

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Current discussions among high-energy physicists are concerned with the energy, costs, location and number of possible new alternating-gradient synchrotrons with energies of over 100 Bev. It is our purpose to explore the extent to which a large-scale experiment, using modern detectors and a budget comparable to, say, a very large bubble chamber, could explore the questions of current interest using cosmic rays.

We consider an array of spark chambers and large magnets deployed vertically above and below a liquid-hydrogen target, and a suitable configuration of triggering counters and electronics. This must be located at a mountain-top cosmic-ray station such as Chacoltaya (Bolivian Andes). (If one chose this site, there would be only 5 mean free paths of atmosphere above the apparatus so that cosmic-ray primaries suffer a factor of 150 attenuation.)

As a particular goal, we shall explore the question of proton-proton diffraction elastic scattering at about 300 Bev and the accumulation of enough data to provide a definitive (± 3% or better) determination of the width parameter for the diffraction peak.

The proposed arrangement (Fig. 1) is a scaled-up version of the recent CERN pion-proton elastic-scattering experiment rotated 90° to accept vertical incoming particles. The basic units are (top to bottom) trigger counters, a pair of spark chambers spaced by 2 meters, a 3-meter

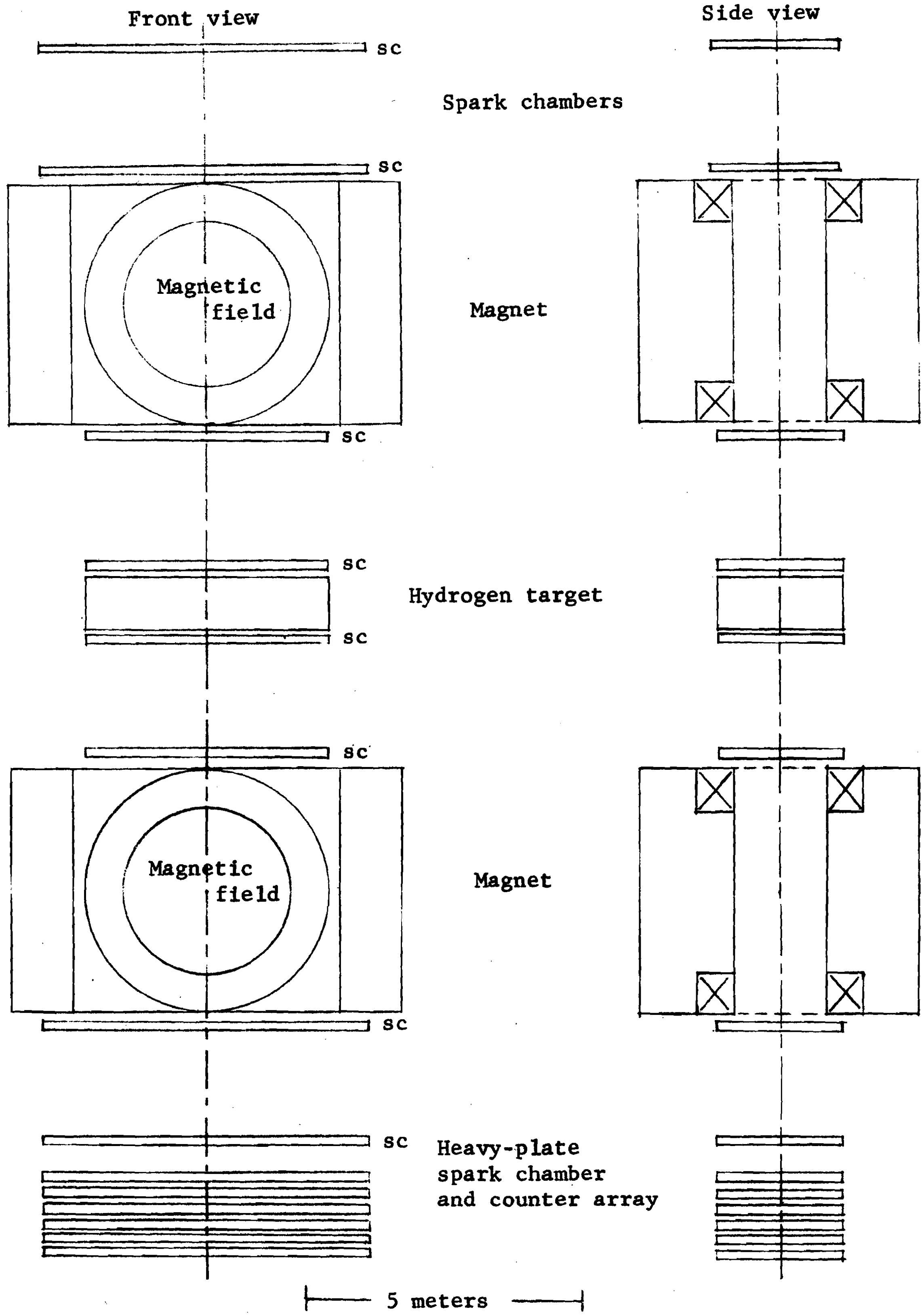

Fig. 1 - Arrangement of spark chambers, hydrogen target and magnets for 300-Bev cosmic-ray experiment

(inside diameter) 16-kgauss Helmholz-coil magnet, a second pair of spark chambers, a liquid-hydrogen target and, below it, an identical array of spark chambers and magnets. At the base of the column would be a heavy-plate spark chamber and counter array to trigger the system only on strongly-interacting particles of greater than a chosen threshold energy.

The spark chambers would be constructed with thin plates (.001 or .002 inches of aluminum) and would contain about 24 gaps per unit. The larger units would be 600 × 200 cm in area. They could reasonably be made of separate smaller units or perhaps have thin, transparent dielectric supports to maintain uniform spacing over the large area of horizontal thin foil. The magnets are modeled after a design of D.I. Meyer in an early proposal for a spark-chamber magnet for the Argonne ZGS. The arrangement is designed to subtend a "large" solid angle.

Above 300 Bev there are about 2.5 cosmic-ray primaries per square meter per second per steradian at the top of the atmosphere so that the flux, Φ, at the apparatus at this location is $1.7 \times 10^{-2}/m^2$ sec steradian The solid angle subtended by the apparatus is determined by the aperture of the two magnets and the distance between them. The bending of 300-Bev particles in the magnets is negligible when computing the solid angle. Assuming that 3/4 of the 3-meter magnet diameter is effective (i.e. produces sufficient bending for use in the data analysis), the effective solid angle of the hydrogen target is one quarter the solid angle subtended at the center of the target. We chose a liquid-hydrogen target with an useful area equal to the useful magnet aperture and with a depth of one meter. A deeper target could be used at a sacrifice of some accuracy due to secondary interactions of the particles in the target. (A 1-meter target is already 1/6 of a proton-interaction mean free path.)

The parameters we have assumed allow one to compute the proton-proton elastic-scattering rate (Table I). In three years about 5000 elastic-scattering events could be collected giving a 2% value to the exponential coefficient in the diffraction-scattering expression $d\sigma/dt = d\sigma/dt(0^{o})\ e^{At}$, where t is the negative of the square of the four-momentum transfer.

The resolution of the experiment depends on the accuracy of locating a track in each spark chamber. Each spark can determine a track (except for delta rays) to about ± 0.25 mm (based on measurements by J. Cronin) so that 24 gaps should make possible a ± 0.05 mm determination. With two such chambers spaced by two meters, the angle of a track segment is then determined to $\sqrt{2} \times \pm 0.05/2000$ or $\pm\sqrt{2}\ (0.025)$ mrad. With the array of spark chambers described, the bending angle in each magnet is known to ± 0.05 mrad and the scattering angle is also known to ± 0.05 mrad. This permits knowledge of the transverse momentum in a scattering to $\pm 0.5 \times 10^{-4} \times 300$ Bev/c or ± 15 Mev/c. However, from the momentum determinations, the inelasticity (e.g. missing mass) is uncertain by $\pm (5 \times 10^{-5}/5 \times 10^{-3}) \times 300$ Bev or ± 3.0 Bev.

There are two weak points in the experiment as described above: the identity of the incoming particle and the missing-mass uncertainty. To improve on these flaws and to increase the over-all utility of the experiment one could add the following auxiliary apparatus. Xenon-gas scintillation counters between spark chambers could aid in identifying positive particles, as to whether they are pions or protons, by virtue

TABLE I

Parameters for 300-Bev Experiment

Primary Cosmic Ray Flux	Φ_o	$2.5/m^2$ steradian sec
Flux at 6000 meters	Φ	$1.7 \times 10^{-2}/m^2$ steradian sec
Magnet parameters		
Coil inside diameter		3.00 meters
Coil outside diameter		4.50 meters
Gap		1.50 meters
Central field value		16 kilogauss
Iron weight		560 tons
Copper weight		100 tons
Power		10 megawatts
Cost (approximate)		$ 1 million
Vertical distances		
Magnet center - target center		5.25 meters
Magnet outer edge - target center		7.50 meters
Solid angle from target center to effective magnet aperture	$\delta\Omega = \delta\Theta\delta\varphi$	$\delta\Theta = \frac{2.25}{5.25}$
		$\delta\varphi = \frac{1.50}{7.50}$
		$\delta\Omega = 8.6 \times 10^{-2}$ steradian
Effective (or average) solid angle over target	$\delta\Omega_E = \frac{1}{4}\delta\Omega$	$\delta\Omega_E = 2.15 \times 10^{-2}$ steradian

TABLE I - Parameters for 300-Bev Experiment (Continued)

Target area:	total A_o	$2.60 \times 4.00\ m^2$
	effective A	$1.50 \times 2.25\ m^2$
		$= 3.375\ m^2$
Target depth		1.00 meter
Proton linear density		$N = 4.2 \times 10^{24}$ protons/cm^2
Cross section for elastic p-p scattering (assumed)		$\sigma_{p-p} = 10^{-26}\ cm^2$
Total elastic-scattering rate		$R = N\ \Phi\ \sigma\ A\ \delta\Omega_E$
		$R = 5.2 \times 10^{-5}$ per second
		$R = 4.5$ per day
		$R = 1640$ per year

of the relativistic rise of ionization. The difference in average ionization of a pion and a proton of 300 Bev/c is 10% and the Landau spread leads to a full width at half-maximum for energy loss in a 2-meter xenon-gas counter of 25%. With four counters above and four counters below the target one could record the pulse heights and compute a probability that the particle is a pion or a proton. Auxiliary spark chambers and/or counters with lead converter plates could be deployed about the hydrogen target to detect γ rays from neutral pions produced in the interactions. Charged pions would generally have enough range to escape the target; however, a proton of momentum less than several hundred Mev/c would stop within the liquid hydrogen. It would be very useful here if a solute could be added to the liquid hydrogen which would scintillate (e.g. one per mil of xenon would be a possibility) so that a pulse would be detected, proportional to the total energy loss in the hydrogen. This would easily solve the problem of separating elastic from inelastic events. Spark chambers could be added within the fields of the magnets, or magnets of lower field might be placed elsewhere in the array, e.g. over the hydrogen target. It has been suggested that, in view of the error in inelasticity, one magnet might be dispensed with, at a considerable saving of cost and effort. However, in this case the quantitative data potentially available on inelastic processes, such as peripheral reactions of various kinds, would be sacrificed. As this could be the most interesting result of such an experiment it would seem sensible to employ both magnets and to determine as much as possible about the incoming and all outgoing particles.

The cost of this experiment has been only superficially considered. The easiest cost to estimate is that of the large magnets. From Meyer's figures, these 3-meter-diameter magnets should cost about one million dollars each. Considering the building to house the apparatus (25-meters high) and to support the magnets, the liquid-hydrogen plant, water-cooling facilities (we are told that water is scarce at mountain-top stations and recirculating systems are essential) and staff, the experiment might cost \$20,000,000, take about 3 years to build and operate for 5 to 10 years. It is important to note that this cost, roughly equivalent to the original CERN PS, is much cheaper than any alternative means of obtaining precise data at such high energies. It is equally important to recognize that the method is very severely limited and that events with cross sections of even a millibarn are collected at a rate less than 200 per year.

If the 300-Bev experiment is feasible, where does the limit lie? The numbers for the 300-Bev experiment have been scaled by a factor of three to explore the possibility of a 1000-Bev experiment. If the linear dimensions are scaled, the solid angle remains (almost) the same and the target area increases quadratically. With 6.0-m spark chamber spacing and the same accuracy, the uncertainty in transverse momentum becomes ± 17 Mev/c and the uncertainty in missing mass becomes ± 3.3 Bev. However, the primary cosmic-ray flux falls off according to

$$\int_{E_o}^{\infty} \Phi(E)\,dE \propto E_o^{-1.8}$$

so that the rate remains essentially constant. The magnets considered for the 1000-Bev experiment are clearly ridiculous; however, on this scale serious consideration should be given to air-core magnets with aluminum coils, cooled with liquid hydrogen. This would greatly reduce power requirements and weight, but would add sophistication and complication. In any case, if the 300-Bev experiment were to cost $20,000,000, the 1000-Bev experiment would not cost less than $100,000,000. At this point, the cost is well above that of adding colliding-beam storage rings to existing machines such as the AGS or the CERN PS. The parameters of such an experiment are summarized in Table II.

We may conclude that it is technically feasible to build a cosmic-

TABLE II

Parameters for 1000-Bev Experiment

Primary cosmic-ray flux Φ_o	$0.3/m^2$ steradian sec
Flux at about 18,000 feet Φ	$2 \times 10^{-3}/m^2$ steradian sec
Magnet parameters	
Field diameter	9.0 meters
Field depth	4.5 meters
Field strength	20 kilogauss
Iron weight	15,000 tons
Copper weight	2,700 tons
Power (conventional construction) without cryogenic cooling	30 megawatts
Deflection of 1000-Bev proton	5 milliradians
Spark-chamber spacing	6.0 meters
Vertical distances:	
Magnet center - target center	13.75 meters
Magnet outer edge - target center	20.5 meters
Over-all height of experiment	58 meters
Target area A_o	5×10 m^2
Effective target area A	4.5×6.75 m^2
Target depth	1 meter
Effective solid angle $\delta\Omega_E$	2.66×10^{-2}
Rate $= N \Phi \sigma A \delta\Omega_E$	6.8×10^{-5} per second

ray experiment capable of making quantitative studies of strong-interaction physics in the neighborhood of 300 Bev. The technique, that of magnets, spark chamber, scintillation counters and a liquid-hydrogen target, would allow the collection of 5000 elastic scatterings in 3 years. However, processes with cross sections much less than a millibarn could not be studied quantitatively. At the level of 1000 Bev the scaling-up of this experiment would appear to cost much more (in time, money and manpower) than the construction of storage rings for an existing accelerator.