Recent Studies on the Experimental Program
Requirements for a Super High Energy Accelerator*

Luke C. L. Yuan

Brookhaven National Laboratory, Upton, New York

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As John Blewett mentioned earlier in his talk that during the early part of this summer, Brookhaven has sponsored a summer program to study possible experimentation with super-high-energy accelerators of ~ 1000 Bev and to examine the feasibility of colliding beam experiments. A group of about fifty physicists took part in this study program. These investigations are a continuation and supplementary to our previous studies⁽¹⁾ at Brookhaven about two years ago.

I shall report on some of the highlights which are of general interest here.

I. Cosmic Ray Results

Since at the present moment, the only reasonable means for estimating what some of the outstanding possibilities may be at 1000 Bev is the Cosmic-Ray studies in the energy region of 1000 to 10,000 Bev; it is highly helpful to ascertain the latest findings in cosmic ray results on high energy collisions. From the studies of the fragmentation of heavy nuclei and the nature of the secondaries produced in jets at energies greater than 1000 Bev in large emulsion blocks, several interesting findings have been obtained by the joint efforts of the University of Chicago, University of Krakow and Louisiana State University as reported by Levi-Setti⁽²⁾. Their work has given us some picture of the inelastic processes for large impact parameter collisions. The essential points of their findings are as follows:

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- (1) the baryons suffer relatively small energy loss in passing through the large block of emulsion (about 20% inelasticity)
- (2) the majority of the pions are emitted from a blob of mesonic matter left behind by the nucleons
- (3) the emission of some very fast pions in the forward or the backward direction at the rate of about 1 per p-p collision.
- (4) there are indications that at very small angles of emission in the center of mass, the transverse momentum decreases in value with decreasing angle. These results are rather significant if confirmed.

$$\theta > 175^\circ \quad \langle p_t \rangle_\pi = 0.22 \pm 0.07 \text{ Bev/c}$$

$$\langle p_t \rangle_K = 0.17 \pm 0.06 \text{ Bev/c}$$

$$\theta < 175^\circ \quad \langle p_t \rangle_\pi = 0.32 \pm 0.05 \text{ Bev/c}$$

$$\langle p_t \rangle_K = 0.44 \pm 0.15 \text{ Bev/c}$$

II. Some Theoretical Expectations on the Experimental Programs for a Super-High-Energy (1000 Bev) Accelerator

The remarks here are based mainly on the report given by R. Dalitz⁽²⁾.

We shall discuss some of the experimental possibilities under the following headings:

(1) Possible Discovery of New Particles.

At the present time, the known quantum numbers do not lead to selection rules which could forbid rapid decay for states of high excitation energy. However, there may well be further quantum numbers for the strong interactions, still to be discovered.

There is increasing belief in the existence of intermediate bosons (both charged and neutral) associated with the weak interactions, with coupling strength intermediate between the nuclear and the beta decay inter-

actions. An example of production of these bosons is as follows:

$$\pi^- + p \rightarrow n + W^0$$

where W^0 is an intermediate boson. These bosons may well be very massive, thus requiring correspondingly high energies for their production.

There is also the possibility of heavy Leptons L , continuing the sequence $e, \mu, \dots$. These heavier leptons would not be seen as decay products, for their parent particles would be so heavy that their weak decay processes would have negligible branching ratio relative to their strong decay processes. These leptons could either be produced directly in neutrino processes, if their coupling happens to be with ν_μ or ν_e or be produced by electromagnetic pair-production processes such as $\gamma + Z^A \rightarrow L^+ + L^- + Z^A$ for sufficiently high γ - energies.

(2) High Energy Collisions Processes.

Among these collision processes we shall discuss two categories of information which are of interest.

(i) Particle structure at small distances, corresponding to impact parameters $\lesssim 10^{-15}$ cm. Information on this question may be regarded as one of the most significant objectives of going up to the super-high-energies. This would mean the study of collisions involving high momentum transfer, say $\Delta \gtrsim 10$ BeV/c with such small impact parameters, $b = \hbar/\Delta \lesssim 2 \times 10^{-15}$ cm, the cross section for all such processes is necessarily small, of order $\pi b^2 \approx 10^{-29}$ cm². The branching ratio for all such processes in p-p collisions is therefore low, of the order of 10^{-4} and so a high intensity beam is necessary.

Further more, it must be emphasized that, for such collisions, it is important to obtain a complete picture of individual events, not only of p-p collision but also of $\pi^\pm - p$, $K^\pm - p$ and $\bar{p} - p$ collisions. Typically, these small-impact-parameter collisions may be expected to lead to one or more final baryons with large transverse momentum, and to a large inelasticity factor with a

relatively high rate for meson production, especially for mesons with a large transverse momentum.

As a specific question we may ask that as the p-p energy rises, what happens to the hard-core repulsion known in the p-p interaction at low energies. Does the outer region of the hard-core become primarily absorptive, leaving a strong elastic repulsion pushed over to smaller distances with increasing energy? Or is the hard-core finite in strength and simply unimportant even at 30 Bev?

(ii) Collisions of large-impact parameter. Here we have first diffraction scattering which reflects primarily the properties of the inelastic processes. At sufficiently high energies, we expect some Regge-pole behavior to set in.

In the long run, the observation of the inelastic processes themselves, may prove to be more illuminating.

As was mentioned earlier in the cosmic ray results, the study of the properties of the blob of mesonic matter, left behind in the p-p collisions, is of particular interest. The interesting question here is the shape and structure of such a blob and what are the fluctuations in its properties. Here again the study of individual complete events will be most informative.

(3) Secondary Beams.

It is reasonable to expect that strong pion beams, well collimated within ~ 1 mr., will be available at very high energies (say up to 400 Bev/c) (at least 0.1 per nucleon incident on the target, in the momentum range 50-400 Bev/c). The cross section and interaction studies possible with these beams constitute one of the major purposes for building such a super-high-energy accelerator.

Furthermore, these pion beams will also give rise to (a) a correspondingly high flux of high energy μ s, up to 200 Bev/c and beyond, making possible

μ -p scattering experiments which is important for their clues to the structure of the μ and the proton. Similarly, (b) there will be correspondingly high fluxes of neutrinos (ν_μ) and anti-neutrinos ($\bar{\nu}_\mu$) at correspondingly high energies for the study of weak interactions. Finally, (c) the corresponding π^0 production and decay will lead to a high gamma ray flux, with strong intensity (at least 0.1 photons per incident nucleon) over the energy range 25-200 Bev making it possible to study very high energy electromagnetic processes.

It is reasonable to expect not only high energy $K^\pm$ beams of appreciable intensity but also to expect that the fast outgoing nucleons may frequently be replaced by outgoing hyperons or hyperon isobars, perhaps at a rate of $\sim 10\%$ per p-p collision. If this proves correct, even short-lived particles like $\Sigma^\pm$ and $\Xi^\pm$ may frequently have appreciable path lengths (of order 1-10 meters) before decay, and studies of hyperon nucleon interactions directly would be possible.

(4) High Intensity AGS (30 Bev) Accelerator.

One of the interesting points developed during the Brookhaven summer study is the possibility of high intensity injection into an AGS accelerator. With an injection energy of 1 Bev, it is expected that the AGS can give rise to a proton beam of 2×10^{13} per second at 30 Bev.

The importance of such high intensities is quite clear for experiments with secondary particles, particularly for weak interaction experiments. For neutrino experiments such an increase in intensity is very crucial--the observation of neutrino induced events in hydrogen is of outstanding importance. One may expect to get 20 neutrino events in the Brookhaven 80" hydrogen bubble chamber, for instance.

III. Colliding Beam p-p Collisions.

The feasibility of colliding beam experiments using storage rings has been studied quite extensively. One must bear in mind of the basic characteristics of storage rings having both certain advantages and certain limitations. The im-

portant advantage is the large center of mass energy available in a colliding beam; but the limitations are that it is essentially a low intensity device with practically no secondary beams available for direct experimentation. Some detailed considerations on the feasibility of p-p elastic and inelastic scattering experiments will be discussed in a later session. I shall only mention here briefly the calculated results of Burhop⁽²⁾ on the momentum and angular distribution of the secondaries produced in p-p collisions. These results are based on a formula given by Cocconi, Koester and Perkins⁽³⁾ and they are of considerable importance in the design of experiments with colliding beams. Figs. 1-4 show these results.

IV. Some Possible Experimental Considerations with a Super-High-Energy Accelerator.

(1) Large Heavy Liquid Bubble Chamber.

A heavy liquid bubble chamber has been considered by W.D. Walker⁽³⁾ which has a dimension large enough so that essentially all of the particles coming from the initial interaction will themselves interact in the chamber. The mean free path for interaction in propane or freon is about one meter so that a chamber in the form of a cylinder 2 meters in diameter and 7 meters in length was proposed. Multiple windows with a diameter of 1 ft. would be provided, and a magnetic field of between 5 to 10 kilograms would be adequate to give an accuracy in momentum measurement of between 30% and 15% for the average strongly interacting track.

The proposed chamber would have an active mass of about 15 tons if filled with a mixture of CF_3Br and ethane.

Such a chamber would be extremely useful in differentiating μ 's and e 's from other particles, thus especially suited for neutrino interacting experiments.

(2) Solid State Detectors and Scintillation Counter Hodoscopes
with On-line Computer.

This topic will be discussed in another paper.

(3) Studies of Radioactivity at High Energies

Serious radioactivity problems can be expected at the high intensity and high energy machines. From experimental results obtained at 30 Bev, Cumming⁽²⁾ and Galonsky have made extensive calculations by extrapolation to 10^{14} protons/sec (16 micro-amps) at 800 Bev (13 megawatts of beam power).

To calculate the induced radioactivities, one has to consider not only the primary beam but also, due to multiplication, a large number of secondaries of about 0.1 to 1 Bev in energy. Assuming a mean energy of 0.25 Bev per secondary, we find 3.2×10^{17} nuclear interactions per second for a beam of 10^{14} protons/sec. However, only a fraction of all such interactions give radioactive products depending on the beam stopper material. In H_2 the fraction is zero. In Li^6 it is close to zero since the major radioisotope produced is the innocuous H^3 . Water might be a good choice when the heat transfer problem is considered. The troublesome activities would be Be^7 (H^3 also produced). With aluminum Na^{22} would also be produced and the combined fraction of long-lived activities is ~ 0.1 . Hence, for aluminum the equilibrium activity is of the order of 0.9 megacuries. This is substantially less than the equilibrium activity of the Brookhaven 25 MW reactor. However, it is essential that the beam be extracted and stopped at some convenient point external to the accelerator.

In practice it will be impossible to extract all of the beam and some of the radioactivities will be produced in specific areas near targets or generally spread around the ring.

A necessary, but not sufficient, requirement for helping cool the 800-Bev tunnel is a pressure of less than 10^{-9} mm Hg.

The choice of construction materials for the accelerator itself is important from the standpoint of induced activity. In heavy materials such as iron there is a wide distribution of yields and many radioactive species. Light elements may be better. However, one will have to use iron for magnets. Aluminum might be used for coils but it turns out that copper may be better as far as long-life radioactivity is concerned.

References

- (1) Experimental Program Requirements for a 300 to 1000 Bev Accelerator and Design Study for a 300-1000 Bev Accelerator, Aug. 28, 1961, Revised Dec. 1962, BNL 772 (T-290)
- (2) Proceedings of the 1963 Brookhaven Summer Study on Super-High-Energy Accelerators and Storage Rings, to be published.
- (3) Future Program for the CERN PS and Brookhaven AGS, Minutes of a Meeting held Sept. 10-14, 1962 at the Brookhaven National Laboratory.

Figure captions

Fig. 1 Intensity of secondaries emitted per unit solid angle per unit momentum range at different angles, θ , to the incident beam.

Fig. 2 Total number of secondaries emitted per unit momentum range per radian at different angles, θ , to the incident beam (i.e. these curves are obtained from those of fig. 1 by multiplying by $2\pi \sin \theta$).

Fig. 3 Intensity of scattered primary baryons per unit solid angle per unit momentum range at different angles, θ , to the incident beam, assuming their transverse momentum distribution is the same as that of the secondaries.

Fig. 4 Total number of scattered primary baryons per unit momentum range per radian at different angles, θ , to the incident beam, assuming their transverse momentum distribution is the same as that of the secondaries (i.e. these curves are obtained from those of fig. 3 by multiplying by $2\pi \sin$).

No. of π -mesons of one sign per Gev/c per
colliding beam interaction per radian
emitted at angle θ to incident proton
direction

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