23 August 1963, Volume 141, Number 3582 SCIENCE

Storage Rings

With moving targets, collision energies much higher than those of present accelerators can be reached.

Gerard K. O'Neill

There are now several particle accelerators in the world with energies in the range of 3 to 30 billion electron volts. Physicists are, in addition, seriously studying designs for accelerators with energies in the range of 100 to 1000 billion electron volts (10^{11} to 10^{12} ev, as usually abbreviated). In the early 1950's, a few physicists began to be concerned about a fundamental limitation which relativity imposes on very-high-energy accelerators. It can be illustrated by the example of collisions in automobile traffic.

When two objects collide (two cars, or two billiard balls, or two protons), the total energy present before the collision is the same as the energy present afterward. Some of it may have been turned into heat, or, in the case of cars, into the crumpling of metal, but the total remains the same. In addition, the momentum stays constant in a collision. At low velocities (low, that is, compared with the speed of light) the momentum of an object is the product of its mass and velocity. Suppose we call the mass of each car M and the velocity of one of them V. Let the other be at rest. Then the total momentum before the collision is

$$MV + M(0), \text{ or } MV.$$

As everyone knows, cars do not bounce very well. If they hit squarely, they crumple up and remain as a single mass of twisted metal. According to the law of conservation of momentum, the total mass after the collision (which is $2M$) times the final velocity of the wreckage (call it W) must be equal to MV. We can express this as

$$2MW = MV.$$

But this means that

$$W = V/2.$$

The question we are interested in is this: How much energy went into crumpling metal and how much was used just in conserving momentum? The energy E of an object is half the square of the velocity, times the mass. Before the collision,

$$E = \tfrac{1}{2} MV^2 + \tfrac{1}{2} M(0)^2, \text{ or } \tfrac{1}{2} MV^2$$

After the collision, the mass is $2M$ and the velocity is W. Then, the energy of motion after collision (E_c) is

$$E_c = \tfrac{1}{2} (2M) W^2$$

$$= MW^2 = M \left(\frac{V}{2}\right)^2 = \tfrac{1}{4} MV^2$$

This is half as much as the original energy. Only the other half, then, $MV^2/4$, went into crumpling the metal.

Suppose that, instead of setting up the collision as we did, we let the two cars have equal velocities but in opposite directions—a head-on collision. In that case, the initial momentum is

$$MV - MV = 0.$$

After the collision, the wreckage stands still. The total energy before the collision was twice that of one car,

$$E = 2(\tfrac{1}{2} MV^2) = MV^2$$

But none of this energy has to be used up in conserving momentum, so in the head-on case the whole MV^2 goes into crumpling metal. This is four times as much energy as in the case where one car stands still.

All of the accelerators in operation at the present time work on the principle of collision of an accelerated particle with a target at rest, like our first example. For low-energy machines, it is not so bad to lose half the collision energy to momentum-conserving motion. But when the accelerator energy is raised higher and higher beyond the $E = mc^2$ "rest energy" of a proton, about 10^9 electron volts, the loss becomes much worse than 50 percent. The reason is that, at high energies, the equations we have used so far are no longer correct. Instead, the formulas of special relativity must be used, and they show that the effect we have discussed causes an energy loss which becomes greater as the energy gets higher.

Table 1 summarizes the situation. In the case of the largest machine so far discussed, a 10^{12}-electron-volt accelerator, only 4 percent of the energy would be available for producing new and interesting reactions. Above 10^{10}-electron-volts (10 Gev) the available energy is proportional to the square root of the accelerator energy.

There is an obvious solution to the problem raised by the relativistic formulas. That is to make particles collide head-on. In that case the available energy is twice the accelerator energy. We can compare the stationary-target and colliding-beam cases by asking what energy a conventional accelerator must have to equal the *available* energy of a colliding-beam accelerator. Table 2 gives this comparison. For the highest energy listed, a stationary-target accelerator must have about 60 times as much energy as the corresponding colliding-beam accelerator if the two are to have the same available energy. We

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cannot get something for nothing in either case, but in the colliding-beam accelerator we get all of the energy we pay for.

In order to permit the carrying out of useful experiments, a colliding-beam accelerator must be able to produce a reasonable number of high-energy particle interactions per second. Here we find a serious problem. If we set up two accelerators and let them direct their beams at each other, we find that the number of interactions is very small. A synchrotron in the 25- to 30-Gev range produces, every 3 seconds, a beam of about 4×10^{11} protons, in an area 1 cm by 1 cm, of length 8×10^{4} cm. The density of protons in the beam is then 0.5×10^{7} protons per cubic centimeter. The area of each proton for interactions, called the cross section, is about 4×10^{-26} cm². For a target length of 10^{3} centimeters, the probability that a collision will occur in a 3-second period is

$$0.5 \times 10^{7} \times 10^{3} \times 4 \times 10^{-26} \times 4 \times 10^{11} = 8 \times 10^{-5}.$$

In this arrangement it would be necessary to wait about 10 hours for even one reaction. In the 1940's a few accelerator designers made calculations of this kind and decided that colliding beams were of only academic interest.

Early in the 1950's a group of accelerator-design physicists began work in a new organization called the Midwest Universities Research Association (MURA). They concentrated on a class of designs called fixed-field, alternating-gradient accelerators. In a fixed-field, alternating-gradient arrangement, the magnetic field is constant in time, and particles change their orbit radius as they are accelerated. In contrast, ordinary synchrotrons have magnetic fields which cycle in time from low to high values. In such machines the particles stay at a constant radius, and the magnetic field remains at its maximum value only long enough to let the beam strike a target. In a fixed-field, alternating-gradient synchrotron, full-energy particles can be accumulated, or "stacked," at a constant radius. It occurred to the MURA designers that two such synchrotrons could be built with a common orbit section (Fig. 1). In that case, particles could be stacked in both synchrotrons, and they would have many chances to interact with one another. In 1 second, the number of traversals of one beam by the other would be just the rotation frequency (about 1 Mcy/sec). This

Table 1. Data for existing and proposed particle accelerators.

Accelerator energy (Gev)	Location of accelerator	Loss due to momentum-conserving motion* (%)
3	Brookhaven, Paris, Princeton	60
7	Berkeley, Moscow	72
25	Geneva	80
32	Brookhaven	81
200	(Under discussion)	92
1000	(Under discussion)	96

* The loss due to momentum-conserving motion as a function of accelerator energy.

would raise the number of interactions per second from 3×10^{-5} to about 3. There would be an additional large factor due to the higher intensity of a stacked beam. The interaction rate would be proportional to the number of particles per cubic centimeter in one beam times the total number of particles in the other. If a thousand accelerated bunches of particles were stacked in each beam, both the number of particles per cubic centimeter and the current would be increased by a factor of 1000, so the product would be 10^{6} times larger. By using this technique, it appeared, interaction rates of 10^{6} per second could be reached. Unfortunately, the special types of machine in which simultaneous acceleration and beam stacking could be carried out would be particularly large, complicated, and inflexible. They would be much more expensive per billion electron volts of energy than other synchrotrons, and their high cost would largely wipe out the cost advantage which could be gained from colliding beams. Largely for this reason, no such machine was ever built.

Early in 1956, while working on the design of the 3-Gev synchrotron at Princeton, I thought of a way to combine the advantages of beam storage and stacking with the comparative simplicity of conventional accelerator design. The time was ripe for such a suggestion—indeed, it was brought forward almost simultaneously by W. M. Brobeck of Berkeley, and a few weeks later by Lichtenburg, Newton, and Ross of MURA. This notion was to build two synchrotron-like guide fields, operating at constant field, near an ordinary accelerator. These extra guide fields, called storage rings, would have a common "straight section"—that is, a region free of magnetic fields and common to the two orbits. Particles brought to the maximum energy of the accelerator would be kicked out, guided through the intervening space, and put into the orbit of one of the storage rings (see Fig. 2). Particles would be stacked in both rings, so that the rate of interaction at the orbit-crossing point could be high.

Table 2. Energy data for colliding-beam and stationary-target accelerators.

Energy of accelerator producing colliding beams (Gev)	Available energy (Gev)	Energy of stationary-target accelerator which would give same available energy (Gev)
3	6	31
25	50	1360
31	62	2040

Since 1956, physicists working at Princeton and at MURA have studied the fundamental limitations under which storage rings would have to operate. First, Symon and Sessler of MURA showed that proton storage rings would be subject to a limit, common to all accelerators, on the density (the number per cubic centimeter) of protons which could be stored.

Limits on the Particle Density

In any synchroton or storage ring, each particle follows, on the average, a path called the "closed orbit." The radius of the closed orbit depends on the particle energy; typically, the vacuum chamber of a storage ring can accommodate a range of particle energies equal to about 3 percent of the average energy. In an accelerator the radius of the closed orbit slowly oscillates at a few kilocycles per second. There is an additional radial motion, called the radial betatron oscillation, which takes place about the closed orbit. Usually the radial betatron motion has a frequency in the megacycle range. We could construct a mechanical analog to this combined motion by hanging a short, light, high-frequency pendulum from the bob of a long, heavy, low-frequency pendulum. The motion of the bob of the smaller pendulum, the superposition of a fast and a slow oscillation, would be the analog of the radial motion of a particle in an accelerator.

There is an additional motion, up and down, called the vertical betatron oscillation. Any particle can, then, be described completely by giving six numbers—the amplitude and phase of each of the three kinds of oscillation for that particle. After particles are injected into a proton storage ring, no changes in their energy take place. Figure 3 shows the amplitude and closed-orbit distribution for a group of particles injected into a storage ring after one acceleration cycle of the injecting synchrotron. The radial position in the vacuum chamber is the sum of closed-orbit and radial betatron positions; it is shown in Fig. 4. Particles whose positions were outside the dashed lines would be lost to the walls.

There is a basic rule of mechanics, called Liouville's theorem, which states that if a group of particles initially occupies the regions represented by the shaded areas of Fig. 3, no additional particles can be put into *all three* of those regions without knocking out the first ones. If we put new particles into the R–R_0 and Z regions that are occupied by the first particles, we must make sure that the new particles avoid the R_0 region that is already occupied. Figure 5 shows how a second group of particles can be added to the storage ring without violating Liouville's theorem. This process, called beam stacking, has been studied extensively, both theoretically and in small model accelerators, by the MURA group. It is clear from Fig. 5 that, in beam stacking, only a certain number of particle groups can be stored.

When storage rings were first thought of, no one had developed ways of transferring particles from an accelerator to a storage ring without severe losses. It appeared that there was room, in the regions represented by the graphs of Fig. 3, for several hundred groups of particles from a synchrotron. However, if each group were to be reduced in number by a factor of 10 or more during the transfer process, there would not be enough stored protons to give a high interaction rate. At first I planned to accomplish the transfer by a method involving energy loss, which appeared to offer a way, in principle, to get around Liouville's theorem. I found, by calculations on a computer, that I could produce a continuous reduction in the area occupied by a particle group in Fig. 3*a*, but only at the expense of a continuous increase in the area occupied in 3*b*. Within a few months, Symon and Sessler of MURA showed that, even in the presence of energy losses, for protons the product of the areas in the R_0 and R–R_0 graphs remained constant. This meant that a very efficient transfer device had to be invented. Fortunately it was possible to develop such a device, and within a year we had a model of it working at Princeton.

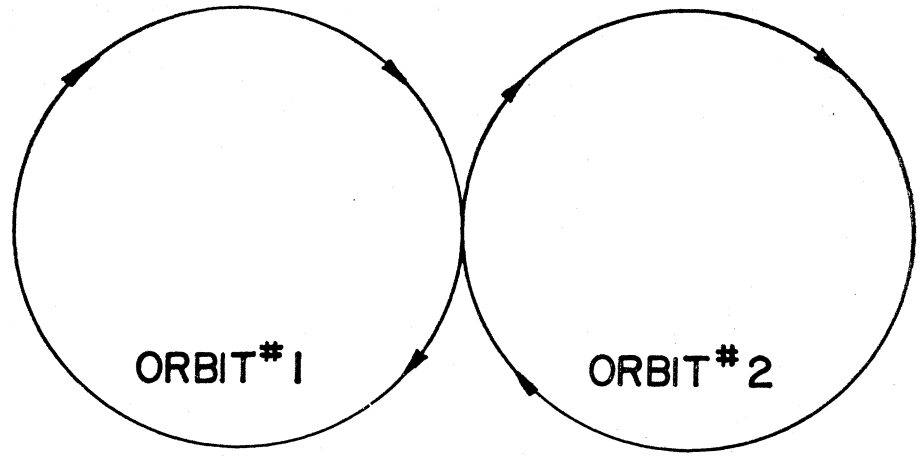


Fig. 1. Basic colliding-beam arrangement.

The second fundamental theoretical point concerned the two ways in which particles were accelerated and stacked. In the MURA machine design the magnetic fields were constant, and particles injected at low energy changed their orbits with time, moving from a low-field region to a high-field one. In the case of storage rings, injection was into an ordinary synchrotron, and, as the particle energy was changed, the synchrotron field increased so that the radius stayed constant. Finally, particles had to be transferred to the storage ring. E. J. Woods and I showed that, in spite of the apparent differences between the methods and the differences in language which had been built up to describe the two kinds of accelerators, the two were subject to the same fundamental limitations. Provided that in each case all the operations were carried out without losses, the ultimate proton densities would be the same. With the exception of these two steps in theoretical understanding, work on proton storage ring design since 1956 has consisted of straightforward calculations, several design improvements, and the study of experimental problems and techniques. In 1960 the European Center of Nuclear Research (CERN) began an intensive study and model program, led by K. Johnsen and A. Schoch. This group has come close to the point of decision on whether to build a 25-Gev storage ring, which would give 50 Gev of available energy.

Electron Storage Rings

In 1956 it became obvious to all of us who had studied the restrictions of Liouville's theorem that they would not apply to electron storage rings. Electrons in a magnetic guide field emit energy, called synchrotron radiation. To maintain the electrons at a constant average central-orbit radius, one must provide radiofrequency energy. The apparatus required is identical to that which is used in an electron synchrotron. If energy is provided in this way, it goes entirely into maintaining the electrons at constant radius. The radiation removes energy from the betatron oscillations and also makes the central

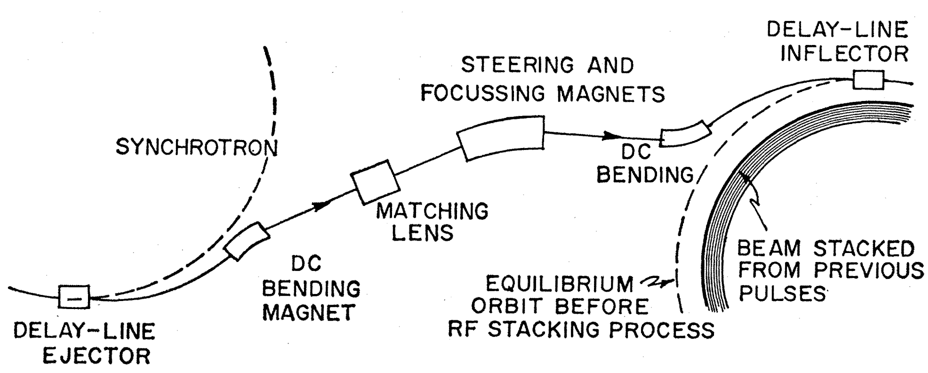


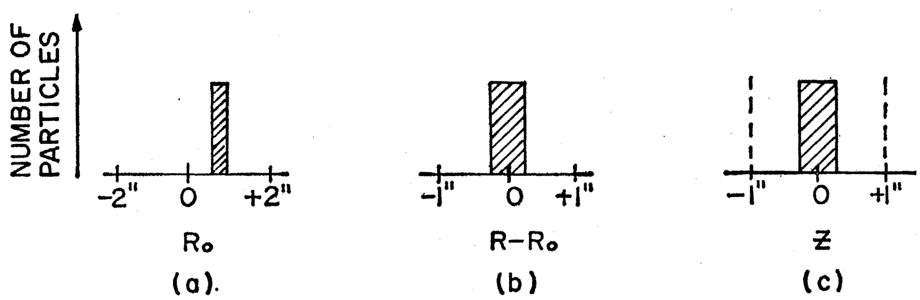
Fig. 2. Transfer from synchrotron to storage ring.

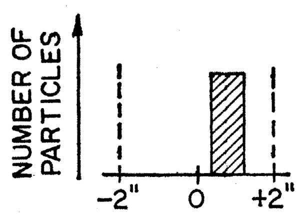
orbit radius R_o approach the center of the vacuum chamber, shown as 0 in Fig. 3*a*. If electrons are injected into a storage ring and their positions are given by graphs, as in Fig. 3, within a few milliseconds the shaded regions shrink to values close to zero. It is possible, therefore, to inject new electrons with a large radial betatron oscillation, let the oscillations shrink, and then repeat the injection process.

Early in 1957 I began studying whether the radiation damping could be used as the basis for a particularly interesting experiment—the high-energy scattering of electrons from electrons. It appeared that this experiment could be the most sensitive, and also the simplest to interpret, of all experiments on the high-energy behavior of electromagnetism. There was also no possibility that it could be duplicated by a stationary-target accelerator. Because of the small mass of an electron, the relativistic loss of available energy is even greater for electrons than it is when protons are the targets. With two electrons, of 0.5 Gev each, colliding head-on, we would have an available energy equal to that of a 1000-Gev accelerator bombarding a stationary electron. The largest electron accelerator operating at that time had less than 1 Gev of energy, and even now the largest electron accelerator has only 6 Gev.

Two graduate students, J. A. Ball and P. Federbush, calculated answers to some of the basic problems. They were aided by a calculation made by R. Christy, of the California Institute of Technology. At first we considered injecting into the storage ring by providing energy losses. This system was simple but appeared quite inefficient. I therefore looked for a way to inject efficiently, and I soon concluded that by building a particular kind of magnet, from ferrite instead of iron, arranged as a delay line instead of an ordinary inductance, and driven by a fast pulse, we could inject electrons quite efficiently. V. Korenman, a senior at Princeton, built a full-scale model of such a magnet, and we pulsed it with a triggered spark gap. It appeared to work properly. With this encouragement I completed the first plans for a colliding-beam electron-electron scattering experiment, to have a total energy of 1 Gev in the center of mass. There remained the question of where to do the experiment (Princeton has no electron accelerator) and how to obtain support for it. The first choice appeared to be Stanford University, which possessed the Mark III electron linear accelerator, the most intense, pulsed, external-beam source of electrons at 500 Mev in the world. Also, the director of the Stanford laboratory, W. K. H. Panofsky, had been very much interested in experiments on the high-energy behavior of electromagnetism. After negotiation with Panofsky during the latter half of 1957, it was agreed that Princeton and Stanford would collaborate on the experiment. W. C. Barber and B. Richter were added as Stanford partners, and B. Gittelman as a Princeton partner. Negotiations for university and government approval occupied 1958, and the construction of the experiment was begun, with support from the Office of Naval Research and the Atomic Energy Commission, early in 1959.

In 1960 a group at Frascati, the Italian national laboratory, became interested in colliding beams. They built an electron-positron single-storage ring, called Ada (for Anneli d'Accumulazione), to operate at a total energy of 0.5 Gev. This group, consisting of Touschek, Bernardini, Ghigo, Corraza, and others, has made rapid progress and has passed some of the important milestones in colliding-beam technique earlier than we have. The differences in the design of these storage rings are mainly in the areas of vacuum technique and the method of injection.





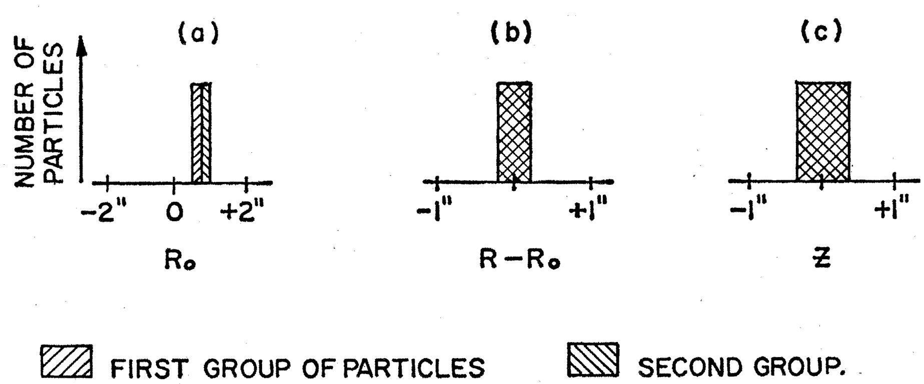


Fig. 3 (top). *a*, Distribution of particles in closed-orbit radius (R_o); *b*, radial betatron oscillation amplitude (R–R_o); *c*, vertical betatron oscillation amplitude (Z). In each graph, 0 is at the center of the vacuum chamber. Fig. 4 (middle). Actual radial positions in the storage-ring vacuum chamber for the particles of Fig. 3. Fig. 5 (bottom). Stacking of two groups of particles brought to full energy in two different cycles of the accelerator.

Ultrahigh Vacuum

There is one component of any colliding-beam apparatus which is essentially different from the corresponding component of an ordinary accelerator. It is the vacuum system, which must be able to produce a vacuum 100 to 10,000 times better than that required for accelerators. At the usual synchrotron operating pressure of 10^{-6} millimeter of mercury, which is about 10^{-9} atmosphere, the lifetime of a circulating beam is only about 2 minutes and there are about 100 times as many gas atoms as circulating-beam particles in a cubic centimeter. In order to build up a large beam it is necessary for the circulating-beam to have a lifetime of at least many minutes. In addition, the large background of interactions in the residual gas makes experiments impractical at pressures of 10^{-6} mm-Hg. To achieve better vacuum, storage-ring vacuum chambers are made of stainless steel; their sections are joined by gaskets made of thin gold rings. Before operation, baking at a temperature of 400°C is necessary, while the pumps continue to operate. If the baking is successful and no leaks open up, an ultrahigh vacuum system may then run for several months at a pressure of 10^{-8} to 10^{-10} mm-Hg. When we designed the vacuum chamber for the electron experiment we were pushing the limits of vacuum technique. Now, however, as a result of major effort by those interested in plasma research and in space simulation, much more is known about ultrahigh vacuum. It seems quite likely that large vacuum chambers, requiring no baking, will be built to operate at very low temperatures. Cryogenic pumping is very effective, and the technology required for it is improving rapidly. It may, however, turn out that future development will be in the form of continuous small improvements of present techniques.

Tests of Electron Storage Rings

In 1962, both Ada and the Princeton-Stanford ring were tested with single circulating beams, and the Ada ring was tested with low-current two-way beams. The test results from the two machines have complemented rather than duplicated each other, since the machines differ in several important respects.

The Ada storage ring, a comparatively small device, accomplishes the injection of electrons and positrons by an inefficient but simple method. A gamma-ray beam made by electrons striking a target passes through the wall of the vacuum chamber. Inside, it strikes another target, producing electron-positron pairs. Some of the particles produced, which according to Liouville's theorem would have to come back to the target eventually, actually miss the target because of the frictional damping caused by their synchrotron radiation. In this way, for every 10^9 original high-energy electrons that hit the external target, about one is injected into a stable orbit. For this sacrifice in efficiency, though, the builders of Ada obtain a great advantage: nothing can go wrong with their injection system, and its simplicity is such that their vacuum can be very good. In 1962 Ada was taken to the Ecole Polytechnique laboratory at Orsay, near Paris. There, with a 1-Bev electron linear accelerator as a source, about 10^6 electrons were stored in Ada. The lifetime for these electrons turned out to be about 80 hours, a value that verified an indicated pressure-gauge reading of about 10^{-10} mm-Hg. If those electrons had made just one circular orbit in that time, instead of their many circuits of a course 7 feet in diameter, they could have circumnavigated the solar system at the distance of the planet Pluto.

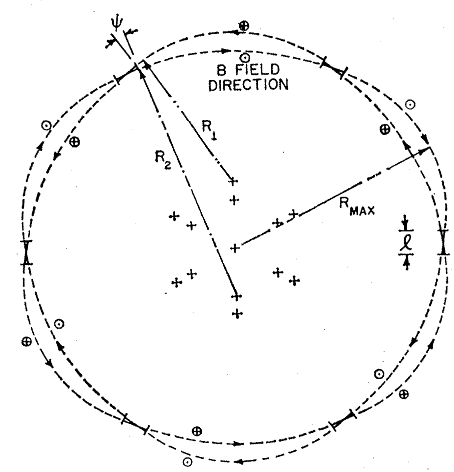


Fig. 6. Orbits of protons in a concentric storage ring. This design provides six interaction regions, at all of which experiments could be simultaneously carried on.

At the time of writing, Ada and the Princeton-Stanford ring have exposed three problems, not foreseen earlier, which will limit but (we now think) not prevent the carrying out of electron-electron colliding-beam experiments. These problems are:

1) *Radiation-induced rise in pressure.* At Stanford it was found that the synchrotron radiation from the circulating electrons caused a rise in the pressure within the vacuum system, from a base of 4×10^{-9} to a maximum of almost 10^{-6} mm-Hg. A maximum of about 5×10^9 electrons were stored within a few minutes. We think that this effect was due to the bombardment by synchrotron radiation of a thin layer of pump oil absorbed on the inner surface of the vacuum chamber. At the time of writing, the pump system of the Princeton-Stanford experiment is being rebuilt with new, oil-less pumps, and the vacuum chamber is being cleaned and rebaked.

2) *Vertical-beam instability.* Normally the passage of a beam through the residual gas in a vacuum chamber liberates positive ions, which remain trapped by the electric field of the circulating negative beam. The Prince-

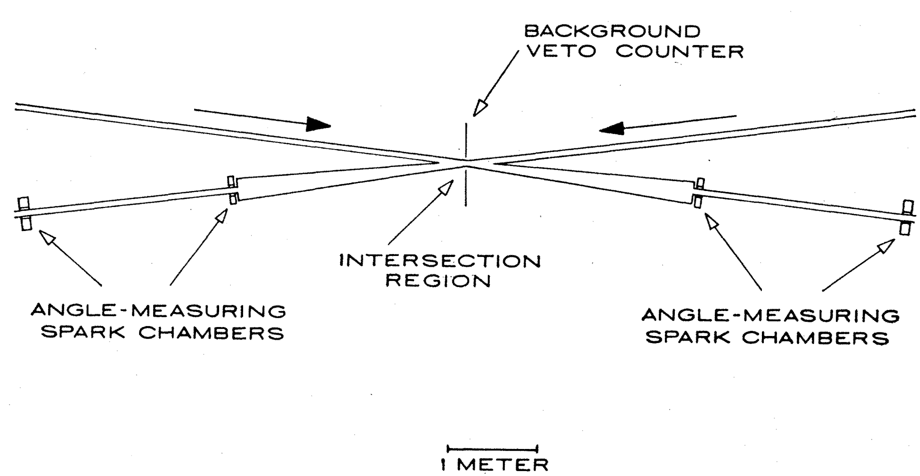


Fig. 7. Experimental arrangement for a 62-Gev proton-proton colliding-beam scattering experiment.

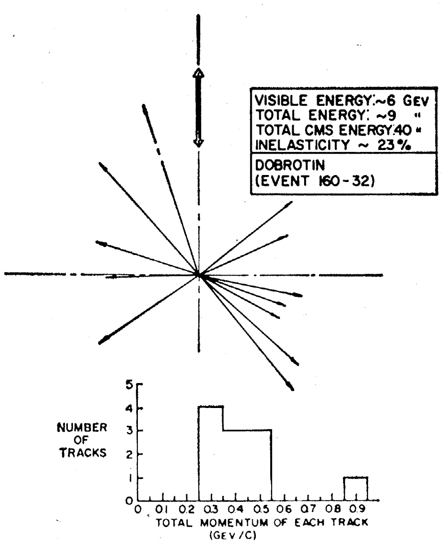


Fig. 8. Evidence obtained from cosmic-ray experiments on the distribution of particles from a 60-Gev collision, as seen in the colliding-beam coordinate system. Momentum uncertainties are about 30 percent.

ton-Stanford ring is, however, equipped with internal, insulated metal plates, called clearing-field electrodes. When these are raised to a high direct-current potential, they sweep out the positive ions. We have found that for the beam currents we have reached so far (about 30 milliamperes), the clearing fields are not needed. When these fields are all turned on, however, and we begin injecting electrons into the ring, the beam becomes unstable when it reaches 5 milliamperes. At that current, strong vertical oscillations suddenly begin, and the beam is lost within a few milliseconds. At MURA a similar effect has recently been found. D. Ritson of Stanford suggested that image charges in the vacuum chamber walls were responsible for it, and A. Sessler of Berkeley has been able to show in detail how image charges can cause the beam losses which are observed. Fortunately, we can reach usable circulating currents without using clearing fields.

3) *The Frascati effect.* In the Ada ring, a beam of about 2×10^7 circulating electrons can be achieved in a time of about 3 hours. Recently the Ada experimenters discovered that, at this current, the lifetime of the beam drops to about 4 hours. B. Touschek of the Ada group has explained this in a simple way, and, despite the present lack of certainty about the first effect, there can be no doubt about the reasons for the Frascati particle-loss mechanism. Touschek notes that the radial and vertical betatron oscillations can cause the particles of a single circulating beam to scatter from each other, transferring a little of the transverse oscillation energy into an alteration of the forward momentum. If the alteration is large enough, particles will be lost from the region of stability for synchrotron oscillations and will strike the walls. The Frascati effect is easy to calculate, and it will certainly limit —probably to 50 or 100 milliamperes —the useful currents which can be stored in an electron storage ring. Although it now appears that currents up to 500 milliamperes could be stored, the lifetime then would be only a few minutes. The resulting continuous loss of particles would lead to background much too high for experimentation. We plan to operate at a current of 25 to 50 milliamperes in each ring, at a pressure which must be kept below 10^{-8} mm-Hg. Under those conditions the lifetime of the beam should be about 1 hour, and our counters should detect about one interaction per minute. It should require only a few hours of operation to measure the electron-electron scattering cross section to within 10 percent (our initial goal). If that experiment goes well, we will increase the accuracy as far as possible; in that case, several days or weeks of useful operating time will be required.

There are plans now to construct, in France, Italy, and the United States, electron-positron storage rings. All of these machines will be designed for studying the structure of elementary particles by the reaction

$$\text{electron} + \text{positron} \rightarrow \text{particle} + \text{antiparticle}$$

In this reaction the "particle" can be anything for which there is sufficient available energy. At 0.6 Gev per electron, for example, the right-hand side of the reaction could be μ, π, or K-mesons. At 2 Gev per electron, any particle now known could be produced in the reaction. It is going to be more difficult to do electron-positron experiments than to do electron-electron scattering, because we have not been able, so far, to make positron beams more than 1/1000 as intense as electron beams. Even so, there is great interest in trying to make positron beams of higher intensity; Table 3 summarizes the plans for construction of electron-positron storage rings. It is too early to say which of these plans will lead to the development of operating storage rings.

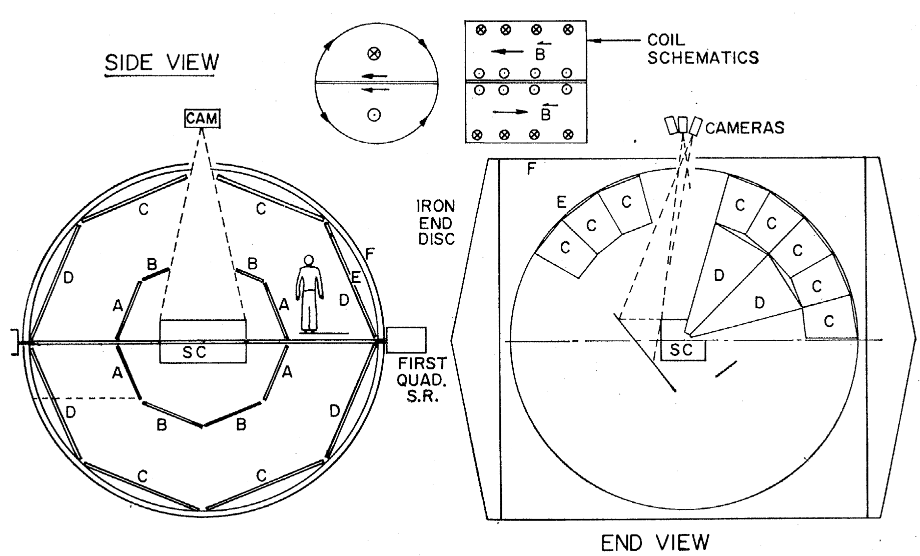


Fig. 9. Apparatus for a 62-Gev experiment on reactions leading to the production of new particles or resonances. *SC*, Main spark chamber; *A*, Sagitta spark chambers, $\theta < 45°$; *B*, Sagitta spark chambers, $\theta > 45°$; *C*, end-point spark chambers, $\theta > 45°$; *D*, end-point spark chambers, $\theta < 45°$; *E*, sphere of time-of-flight counters; *F*, analyzing magnet coils.

Colliding Proton Beams

The experiments which are being attempted with electron-electron or electron-positron colliding beams are unique, in the sense that no reasonable stationary-target experiment could ever duplicate them. A 1000-Gev electron linear accelerator which could do the equivalent of our first storage-ring experiment would have to be 40 miles long and would cost 3 billion dollars. It is possible, however, to extend the synchrotron principle of acceleration to very high energies for protons only.

Moreover, the available energy is much higher for proton-proton than for electron-electron experiments, given the same accelerator energy. As a result, the first storage rings for protons would have an available energy comparable to that of synchrotrons we can now imagine building. The parameters of a proton storage ring and a conventional synchrotron can best be compared if we choose, as a ring injector, the highest-energy synchrotron now operating—the Brookhaven alternating-gradient proton synchrotron (31 Gev) (see Fig. 6). With this synchrotron the available energy for a 31-Gev storage ring would be 62 Gev. The cost of the storage ring would be $50 million. A stationary-target synchrotron having the same *available* energy would require a synchrotron energy of 2040 Gev and a diameter of 10 miles. The cost would be $1400 million. The largest synchrotron design which has so far been studied has energy, diameter, and cost just half those of the 2040-Gev machine.

Thus, the storage ring would have a great cost advantage relative to the conventional synchrotron, but it would be subject to several restrictions, particularly on particle type and rate of interaction, from which the conventional machine would be free. For this reason there has been much discussion about the advisability of building a 31-Gev storage ring. No one is yet familiar

Table 3. Data for electron-positron storage rings now in the planning stage.

Energy per electron (Gev)	Location
0.5–0.6	Stanford
0.45	Orsay (France)
0.75	Frascati (Italy)
1.5	Frascati (Italy)
3.0	Stanford

with colliding-beam experiments, and there is a natural reluctance to do, in a new way, experiments which are already difficult enough when done in the old way. So far only Lawrence Jones, of the University of Michigan, and I have looked hard at the question of how to do experiments with colliding proton beams. We have studied in some detail several possibilities which appear particularly interesting.

Three Proposed Experiments

1) *Elastic and near-elastic proton-proton scattering*. This experiment is of great interest for strong interactions, as is electron-electron scattering for electromagnetic interactions. In Fig. 7 is shown an arrangement of counters and spark chambers by means of which protons scattered at the angles of particular interest, 1 to 3 degrees, could be detected. A circulating current of about 0.5 ampere per ring would be used, giving about 100 colliding-beam interactions per second. In the circulating beams, the angles of proton orbits would be known to about 0.1 degree, and the energy, to about 0.1 percent. With a vacuum of 10^{-10} mm-Hg, the rate of background reactions anywhere within 30 feet of the target point would be one per 200 microseconds. Under these conditions the rejection of background by the electronic circuits would be quite easy.

2) *Study of new particles or resonances*. Within the past 2 years it has been found that there are a number of resonance states of very short lifetime (about 10^{-21} sec) which are produced in energetic collisions and which decay into ordinary particles. They are detectable only from the correlations in momentum, angle, and particle type among their decay products. If we reach higher energies than are now attainable, there is good reason to believe that many, perhaps all, of the new particles found will be of this short-lived kind. It is therefore necessary that we have a way to detect and identify *all* of the charged particles that come out of a single reaction. If we see only one or two particles from each reaction, we may never know that a resonance is present. Figures 8 and 9 show a design for an experiment of this kind. The apparatus includes a very large magnet, several thousand counters

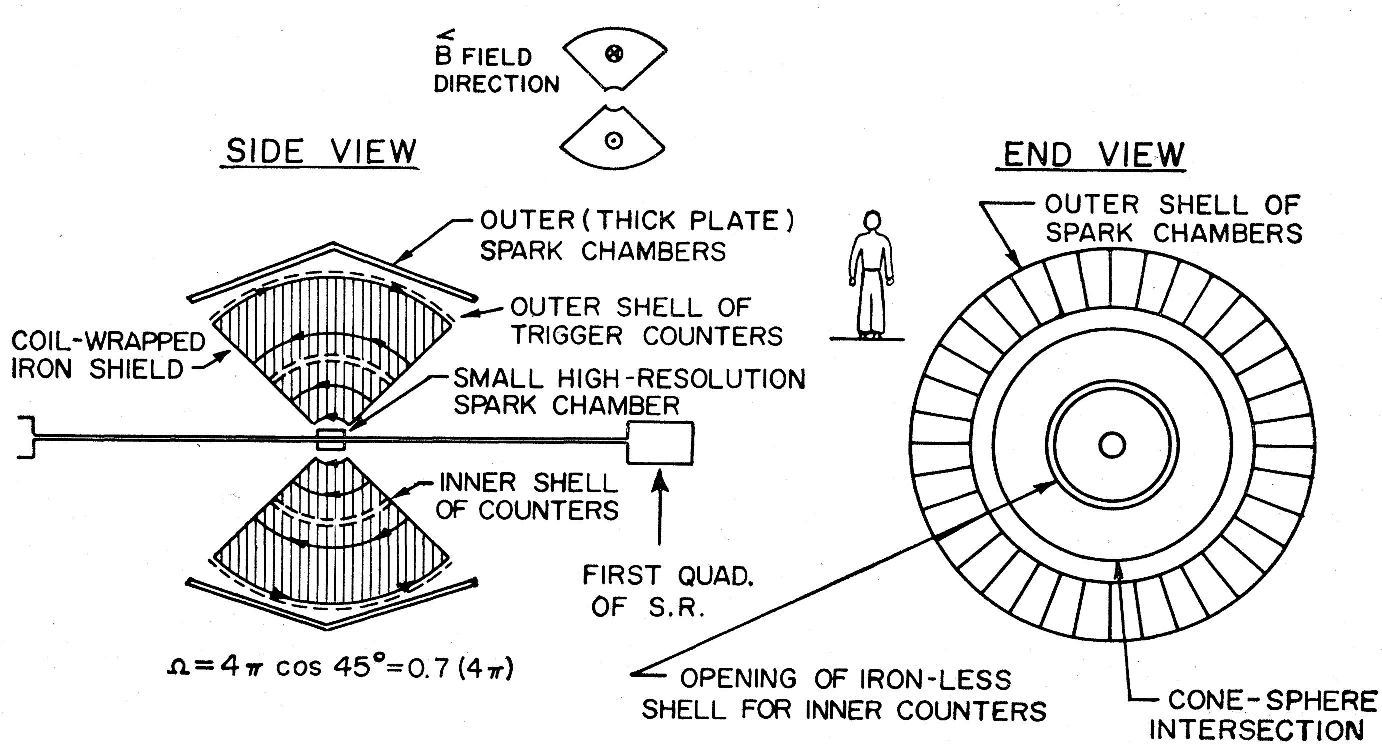


Fig. 10. Arrangement for a 62-Gev experiment on a short-lived intermediate particle decaying into a μ-meson and a neutrino.

of a simple type, and many spark chambers. For most of the inelastic colliding-beam interactions, the momentum of every charged particle coming out would be measured to within 0.25 percent and the flight time would identify the particle as a proton, a π-meson or a K-meson. The circulating currents and interaction rates would be comparable to those of experiment 1, but only the collisions that produced large numbers of decay particles would be recorded. The enormous amount of information obtained from this experiment would have to be analyzed by computer, as is customary for bubble-chamber experiments at the energy now obtainable.

3) *Search for the intermediate boson.* At present there is considerable excitement among high-energy physicists about the existence of a particular new particle. It is a shortlived resonance, if it exists at all. If it is found, it will help explain the field of weak interactions, to which the recent Columbia-Brookhaven neutrino experiment and the parity-nonconservation experiments belong. Perhaps the intermediate boson will be found with existing accelerators. If not, it will only be because the mass of the boson is too great for it to be produced at the energies now available. In that case, it should be found in the experiment of Fig. 10, through decay of the boson into an energetic, penetrating μ-meson. The heart of the apparatus is a magnetized iron shield, which will attenuate all charged particles except μ-mesons and permit rough measurement of the energy of the particles which pass through. This experiment, if still necessary when the first proton storage ring is completed, will require a circulating current of 5 to 20 amperes per ring. It appears that such currents can be stored and will survive for several hours. At a pressure of 10^{-10} mm-Hg, the background rate in this experiment would be one interaction per 5 microseconds. This is low enough for rejection by the electronic circuits to be possible.

At present there are only a few of us who are actively working on storage-ring experiments. We enjoy being in a new and exciting field, and we hope that this technique will be strengthened by ideas from many more physicists.

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Biological Mechanisms Underlying the Aging Process

The ideas and techniques of genetics are being used to obtain new insight into the problems of aging.

Howard J. Curtis

The phenomenon of aging is one with which every child is familiar. Everyone realizes that he will undergo adverse changes, with the passage of time, which will eventually lead to death in one form or another, and accepts this as inevitable. It is difficult to think of a biological process of more interest to most adults, and yet through the years the explanations for this phenomenon have mostly been couched in vague generalities. Even today gerontologists cannot agree upon a definition of aging.

It would be quite impossible in one brief article to cover the vast literature on the subject or discuss even a fraction of the theories of aging. However, an attempt will be made to present recent ideas and experiments on this subject in the light of modern biological thought.

Clearly, aging is not merely something which leads to death, for acceptance of this idea would lead to such absurd conclusions as, for example, that automobiles are causing aging in the American population because they are decreasing the life expectancy. In this context, diseases and even cancer might be put in the same category as the automobile, and the question then arises, What is left? Certainly the organism continually "runs down," and which disease finally causes death is often merely a matter of chance. The phrase "died of old age" is no longer in vogue, but the idea behind it is still pertinent. On this basis it seems reasonable to define aging, as Comfort does (*1*), as a biological process which causes increased susceptibility to disease. There are some obvious exceptions, but as a generalization this definition seems to stand up reasonably well. Even cancer and atherosclerosis would then be considered biological phenomena separate from the phenomenon of aging. Thus, senescent tissue provides a favorable environment for some diseases, such as cancer, and withstands the stress of other diseases less well than younger tissues do.

On this basis, then, one must ask what the nature of senescent tissue is and what causes the change from young to old tissue. The many theories which have been put forward to account for aging have been discussed in a number of recent publications (*1*, *2*) and are dealt with only briefly here, under three general categories.

First is the group of theories which postulates the accumulation of deleterious products of metabolism as a cause of aging. Certainly products such as collagen accumulate in some tissues and give these organs the appearance of old organs. The skin is a familiar example. Accumulation occurs in some tissues very markedly and in others practically not at all. Further, organs like skeletal muscle which show little, if any, ac-

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