The Proton Synchrotron

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IN 1910 AND 1911 Geiger and Marsden performed a series of experiments designed to reveal something of the structure of the atom. They directed a collimated beam of alpha particles through a thin gold foil and observed the distribution in direction of the emerging particles. Although most of the particles were scattered through small angles they found that some suffered very large deflections—indeed, about 0.01 percent of them were deflected through angles greater than 90°. This was completely inconsistent with any kind of continuous structure of the atom—as, for example, a homogenous distribution of positive charge with imbedded electrons. Rutherford proposed a very different model, in which the positive charge and most of the mass were concentrated in a central sphere one ten-thousandth the radius of the whole atom. Occasional close collisions of the impinging alpha particles with this central nucleus would result in large deflections, and it was thus possible to explain quantitatively the experiments of Geiger and Marsden. This was the beginning of our modern theories of atomic and nuclear structure. Since that time and especially since 1930, a large part of nuclear physics has consisted of further probing of the nucleus with beams of various particles to reveal its structure and properties. However, even an outline of the developing ideas of nuclear physics is beyond the scope of this article, which is concerned only with the means of providing the probing particles.

Naturally occurring high energy particles (except for cosmic rays) are limited to the alpha and beta particles of radioactive substances whose energies are a few million electron volts. As nuclear experiments continued, higher energies and more kinds of particles were needed. Experimenters also found they were hindered by their limited control over the direction, intensity, and energy of natural particles. To fill these needs, a series of particle accelerators were developed, as outlined in Table 1. Development of the first three was carried to the point of successful application to nuclear physics in the early 1930's. The betatron dates from 1940. The next three became useful machines in 1946, 1947, and 1948. All of these machines are still being developed and with their varying energy ranges, intensities, suitability to different particles, and degrees of control, each one

TABLE 1

Accelerator	Particle*	Highest energy of operating equipment in Mev†	Highest energy of equipment under construction in Mev	Remarks
Electrostatic accelerator	Any charged particle	5	12	Capable of precise energy control and collimation. Limited to the lower energy range because voltage is applied in one step.
Rectifiers or transformers	Any charged particle	2		Similar to the electrostatic accelerator.
Cyclotron	p d α	10 20 40	 30 	A reliable and economical accelerator in the medium energy range. Limited to energies of a few 10's of Mev by the relativistic mass increase.
Betatron	e	100	300	For electrons only. A simple machine in the medium energy range but limited by radiation loss to several hundred Mev.
Synchrocyclotron	p d α	350 190 380	450	This machine overcomes the energy limitation of cyclotron but becomes uneconomical above 500 Mev. Beam intensity is lower.
Linear accelerator	p e	32 25	66 1,000	The energy is unlimited. It has the advantage over magnetic machines that the beam emerges in a well-collimated bundle with a small energy spread.
Synchrotron	e	335	1,000	Raises the energy limitation of the betatron.
Proton synchrotron	p	6½	3,500	The energy limit is the economic one but it is higher than that of the synchrocyclotron.

* Particles: p, proton or hydrogen nucleus; d, deuteron or heavy hydrogen nucleus; α, alpha particle or helium nucleus; e, electron.

† Mev, 10^6 electron volts.

supplements rather than replaces its predecessors.

As increasing effort has been made to understand the nature of cosmic rays they have been revealed as a rich source of particles useful for nuclear investigation. These observations have already yielded the positive electron and a growing family of mesons, and have provided the experimental background to a number of advances in electrodynamic theory. Cosmic ray particles may have energies up to 10^{16} electron volts, assuming that extensive Auger showers are initiated by a single primary particle. They strike the earth's atmosphere at a rate of about 0.6 per cm^2 per second, and consist chiefly of protons, although it has recently been shown that a few percent of them are nuclei of various atoms up to at least the middle of the table of elements, with the possibility that all nuclear species are present. As the particles pass through the atmosphere they interact with atmospheric nuclei, sharing their energy with existing particles and creating new ones. Cosmic radiation below the top of the atmosphere is therefore an exceedingly complicated mixture of interrelated particles and quanta. It is desirable, in the energy range where it can be done, to supplement cosmic rays with laboratory-produced radiation so that conditions can be controlled and simplified. The artificial source can also have much greater local intensity. It is here that the proton synchrotron fits into the scheme of things. Projected machines are in the range 1 to 6 Bev (billion electron volts). The average energy of primary cosmic ray particles is 10 Bev; thus the lower range of cosmic ray energies is nicely covered, but the upper range to 10^{16} electron volts is a million times higher than that which will be reached by accelerators now being built.

A limitation is imposed upon cyclotron energies by the particles' relativistic increase of mass as they are accelerated. This can be readily seen as follows. An ion in a uniform constant magnetic field of B gauss describes a circular path of r cm radius such that

$$Br = \frac{v}{e/m}$$

where $\frac{e}{m}$ is the charge-to-mass ratio of the ions and v is the velocity. From this we can write for the time per revolution,

$$t = \frac{2\pi}{e/m\,B}$$

This is essentially a constant in the nonrelativistic range; hence an alternating electron field of frequency $1/t$ applied to a diametrical accelerating gap will give an incremental acceleration each revolution to ions starting in the proper phase. However, the mass changes with the velocity according to the relationship $m = \frac{m_0}{\sqrt{1-\beta^2}}$, where m_0 is the mass of the ion at rest and β is the ratio of the velocity of the particle to that of light. If then the particle is accelerated until its velocity is half the velocity of light (the energy of a proton with this velocity would be 150 Mev), the mass is 15 percent greater than the rest mass and the time t is 15 percent greater than for the first turn. Under these conditions the ions would get out of phase with the accelerating field and would not be accelerated.

The theory of the synchrotron—electron or proton—and the synchrocyclotron which circumvented this difficulty was worked out independently by V. Veksler (*11*), E. M. McMillan (*6*) and M. L. Oliphant (*7*) and depends upon the phase stability of an ion in a magnetic field under certain conditions. Suppose that we have an ion in the extreme relativistic energy range pursuing a circular path of radius r in a uniform magnetic field, and that we apply a voltage of the proper radiofrequency as before, but suppose it to be of such phase that the voltage goes through zero as the ion crosses the accelerating gap and that an earlier crossing of gap will result in acceleration.

The radius is given by:

$$r = (E^2 - E_r^2)^{\frac{1}{2}}/300\,B$$

(*6*), where E is the total energy $= E_k + E_r$,

E_r is the rest energy = 935 Mev for proton,
E_k is the kinetic energy.

The expression may then be rewritten in the form

$$r = (E_k^2 + 2E_kE_r)^{\frac{1}{2}}/300\,B.$$

If E_k is large compared to E_r

$$r = E_k/300\,B, \text{ approximately.}$$

Thus in the relativistic range the radius is proportional to the energy and the velocity approaches the constant velocity of light. Earlier arrival at the gap results then in greater energy and a longer circular path but little change in velocity and hence the particle will be later in crossing the accelerating gap the next time. Conversely if it were to arrive too late it would be decelerated, pursue a shorter path, and catch up in time. The particle, if disturbed in phase, then oscillates about the stable phase, where it gains no energy in crossing the gap. These arguments for stability of phase are not valid at low energy but the same kind of stability can be achieved by having the magnetic field decrease radially. This is desirable anyway, to keep the ions in the median plane of the magnetic field. If the magnetic field or the frequency of the accelerating field or both are slowly changed in the proper direction the energy of the particle will increase and the stability will hold for the phase such that just enough energy is gained during each revolution to keep step with the changing field or frequency. In addition to the phase oscillation, which is slow compared to the rotational frequency, there are also radial and vertical oscillations in position, comparable with the rotational frequency. They are known as the betatron oscillations.

Several different accelerators have been devised on the basis of the principle of phase stability. The distinction between them depends upon which parameters are varied. In the case of electrons no change of frequency of the accelerating field is required if the particles are given 2 Mev or a little over by some other means because they then have 98 percent of their limiting velocity. The magnetic field is increased with time to hold the orbit radius constant. The vacuum tank is toroidal and the magnetic field fills an annular space. This machine is a synchrotron. There are two possibilities in the case of heavy ion acceleration. In the first the magnetic field is constant and has the same configuration as for a cyclotron. The ion source at the center and the accelerating dee is also the same but the frequency of the accelerating voltage decreases as the mass of the ions increases and their period of revolution increases. The orbit radius increases so that the total path is a close-pitched spiral. This machine is a synchrocyclotron. As accelerators of this type are made larger an economic limit is approached at 500 to 1000 Mev, chiefly because of the very large magnet structure required. The remaining possibility is that the magnetic field as well as the frequency should vary. The orbit radius can then be held constant, requiring only an annular magnet, which is very much cheaper than the corresponding cyclotron type of magnet. Three of these proton synchrotons are being built at present. One, at the University of Birmingham, England, is designed for 1.3 Bev. Another, under construction at the Brookhaven National Laboratory, will accelerate protons to about 3 Bev and is called a cosmotron. A third is building at Berkeley and will initially operate at 3½ Bev but it can be modified to produce protons of about 6 Bev. This machine has been named a bevatron. The only physical limit to the energy of this class of accelerator is that imposed by the loss of energy due to the electromagnetic radiation from a charged particle moving in a circular path. For protons, this limit is so high that the cost, which is one to two million dollars per Bev, is the governing limitation. The theory of the proton synchrotron is given in detail in references *3* and *10* and proposals for their construction are outlined in *1* and *7*.

The basic design of the Berkeley bevatron stems from the proposals of W. M. Brobeck (*1*). The magnet will consist of four 90° annular segments spaced so that the ion orbits are quarter-circles connected by straight sections. That magnet arrangement was first proposed by H. R. Crane (*2*) for a synchrotron he is now building. Provision is made in the straight sections of the vacuum tank, between the magnet segments, for evacuating the tank, injecting the beam, placing the accelerating electrode, and performing experiments with the beam. Magnet power will be provided by a motor generator with a large flywheel. During build-up of the magnetic field, energy will be drawn from the flywheel and stored in the magnet. As the field is reduced the generator acts as a motor and returns energy to the flywheel. The motor makes up only the losses, which for each pulse amount to 40 percent of the stored energy. It is intended that the protons will be injected at 10 Mev from a linear accelerator. Some of the dimensions, as finally settled upon, are given in the first column of Table 2.

TABLE 2

	Bevatron now being constructed	¼ Scale model now completed
Proton energy	$3\frac{2}{3}$ Bev	$6\frac{1}{2}$ Mev
Number of protons per pulse	10^{10} or more	$2 \cdot 10^{8}$
Pulse rate	10 per minute	18 per minute
Orbit radius	48½ feet	11½ feet
Length of straight sections	20 feet	5 feet
Cross sectional aperture of useful magnetic field: vertical	24 inches	9.5 inches
radial	72 inches	36 inches
field: vertical radial		
Number of revolutions during acceleration	$3.8 \cdot 10^{6}$	$0.9 \cdot 10^{6}$
Distance traveled during acceleration	270,000 miles	15,000 miles
Acceleration time	1.75 second	0.25 second
Maximum magnetic field	9,800 gauss	1,000 gauss
Magnet weight	10,000 tons	150 tons
Energy stored in magnet	$8.3 \cdot 10^{7}$ joules	$4 \cdot 10^{4}$ joules
Magnet operating power	6,000 kilowatts	30 kilowatts
Acceleration radiofrequency	0.37 to 2.5 megacycles	0.4 to 1.2 megacycles
Injection energy	10 Mev	0.7 Mev

Before the design entered the final stage there was some uncertainty as to whether or not the theory could be trusted in detail. In particular, no machine had yet run with straight sections as proposed by Crane, and it was conceivable that an unforeseen perturbation would introduce ion oscillations large enough to drive the beam into the tank walls. There was also the very important question as to just what would be a reasonable cross section for the useful magnetic field. Obviously, there are conflicting factors. With a given investment in magnet and excitation equipment one could have a small aperture with high field, which would give high energy particles but would permit only very limited deviation from ideal ion orbits. On the other hand, choosing a large aperture would lower the final energy. Turning the injected ions into their orbit requires some kind of electrodes that extend into the tank, and many of the ions on subsequent turns will be intercepted by this structure. We were not sure what fraction could be made to escape this fate.

To answer questions such as these and to provide general operational experience it was decided to build a working model on ¼ linear scale. Since nearly all of the things that might go wrong should occur soon after injection, about 6-Mev acceleration was considered sufficient. This, of course, made the model very much cheaper in terms of magnet and excitation equipment. The second column of Table 2 gives the essential dimensions of the model.

The general structure is shown in Fig. 1. To de-

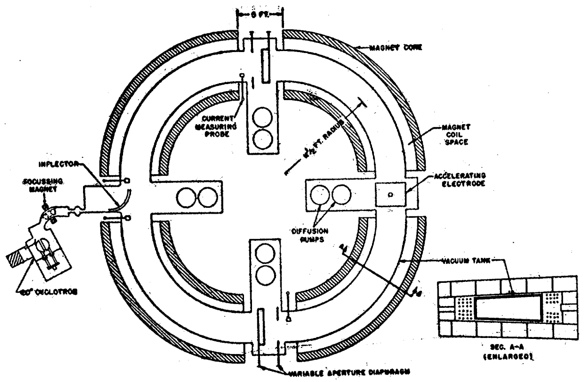

FIG. 1. Diagram of the ¼-scale operating model bevatron.

crease eddy current effects the magnet structure is made of ½-inch plates separated by paper insulation, and for the same reason the vacuum tank is made of 1/32-inch stainless steel in sections about 1 foot long, each section sealed to the others but insulated from them by rubber gaskets. The atmospheric load on the tank is transmitted by attachment bars to the magnet yoke. Fig. 2 is an over-all view, with the injector cyclotron in the foreground.

The protons are accelerated to 0.7 Mev in a cyclotron which operates for one millisecond and is triggered by the bevatron magnet current as it reaches the proper value. The ions pass through a focusing magnet and then as they enter the bevatron magnet they are turned by the electric field of the inflector electrodes so that they are tangent to their bevatron orbit. As the magnetic field increases, but with no energy added to the ions, they oscillate about circular paths of decreasing radius. Before they all reach the inner tank wall the accelerating electrode is excited with a frequency equal to the rotational frequency. This electrode is in the straight tank section opposite the inflector and is an open-ended copper tube placed so that the ions go through it. The energy given to the protons is equal to the change in voltage on the electrode during the traversal, since the electric fields at the two ends are opposite in direction. In the model bevatron the protons are given about 40 electron volts per turn to keep step

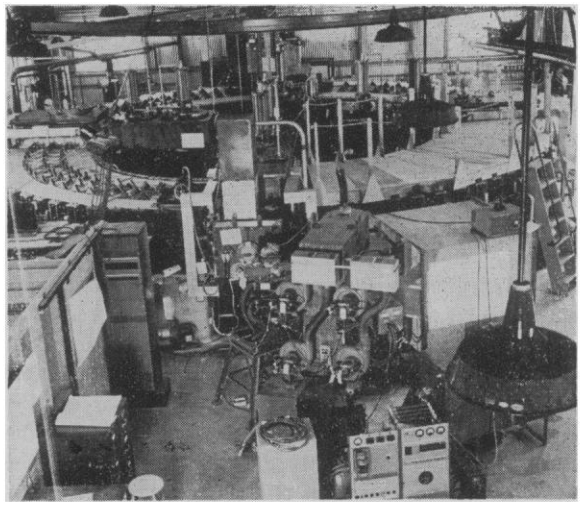

FIG. 2. Photograph of the model bevatron showing the injector cyclotron in the foreground.

with a magnetic field increasing at 4000 gauss per second. Since the ions are well out of the relativistic range the velocity and hence the rotational frequency is proportional to the momentum of the particles. The momentum of a particle at constant radius is proportional to the magnetic field; hence the applied radiofrequency must vary as the magnetic field. This variation in frequency is accomplished by passing a portion of the magnet current around the fer-

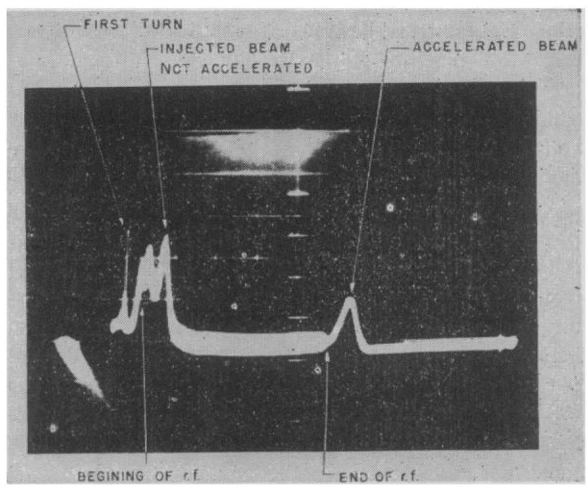

FIG. 3. Oscilloscope trace of bevatron beam. Horizontal divisions are 2 milliseconds; vertical divisions are 0.8×10^{-7} amperes.

romagnetic core of the inductance in the radiofrequency circuit. The increasing saturation of the core as the magnet current increases lowers the inductance and increases the frequency of the circuit.

The required frequency range is from 0.4 to 1.2 megacycles per second. In about one quarter of a second the magnetic field has nearly reached its limiting value of 1000 gauss and the protons have an energy of about 6½ Mev. The radiofrequency is cut off, a further small increase of magnetic field decreases the orbit radius, and the ions are intercepted on a probe introduced through the inside wall of the annular tank. The oscilloscope trace, Fig. 3, shows

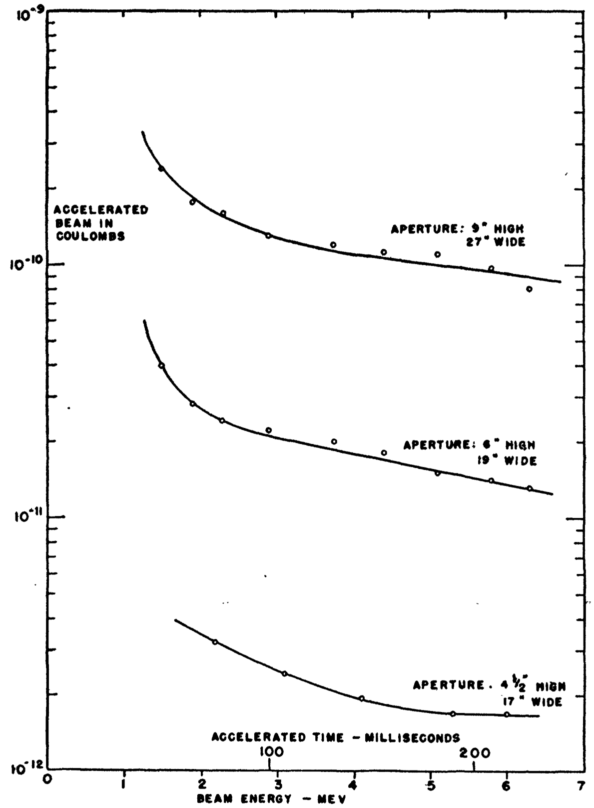

FIG. 4. The beam as a function of final energy for three tank apertures.

the history of a single pulse; in this case the acceleration lasts for only 10 milliseconds so that the entire pattern can be shown. Ions of the wrong energy or direction hit the probe on the first turn. Of the surviving ions, those that cross the accelerating electrode in the right phase are accelerated. Those in the wrong phase are driven into the probe immediately after the radiofrequency is turned on.

In their long path in the bevatron the ions suffer many collisions with the residual air molecules in the tank. Note from Table 2 that the ions in the bevatron and the model are accelerated for 1.75 seconds and 0.25 seconds, respectively, as compared to 0.002 seconds in the 184-inch synchrocyclotron. The combined effect of many such collisions during this long acceleration, particularly just after injection when the energy is low, causes a substantial loss of beam. We found that an increase of pressure of 1.7×10^{-6} mm Hg resulted in a decrease of the beam by a factor of $1/e$. This agreed with the expected loss within the accuracy of the theory and the measurements. The usual operating pressure was 2×10^{-6} mm. The decreasing loss of beam at greater energies is shown in Fig. 4. Here the final energy is adjusted by changing the duration of the accelerating radiofrequency pulse and recording the integrated beam picked up on a probe with a constant injected pulse. Most of the loss occurs at energies less than 3 Mev. Using the adjustable aperture diaphragms provided in two of the straight tank sections, these data were taken for three cross sections. The middle curve most nearly corresponds in relative size to the 24-inch-high, 72-inch-wide aperture chosen for the full-size bevatron.

The betatron oscillations of the ions in the radial and axial directions are approximately given[1] by

$$f_r = \sqrt{1-n}\, f_0$$

$$f_a = \sqrt{n}\, f_0$$

where n expresses the radial decrease of the magnetic field $n = \frac{r}{B}\frac{dB}{dr}$ and where f_0 is the rotational frequency. The constant, n, equals 0.6; hence both frequencies are near to the rotational frequency. It is very important that there be no simple harmonic relation between these frequencies. If there were, the amplitude of one of the oscillations might build up until the ions were lost to the tank walls. These frequencies were measured by an experiment suggested by H. R. Crane, in which a radiofrequency field is established in a radial or axial direction across the vacuum tank. At the proper frequency it will increase the oscillations and destroy the beam. The calculated frequencies were verified to about 1 percent.

Some things of interest were learned which are not yet quantitatively explained. Two of these effects apply to the critical period of injection. It was

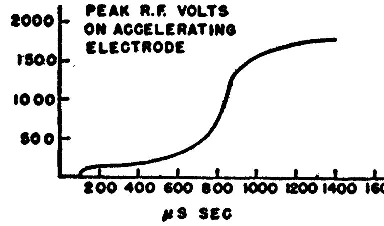

FIG. 5. Optimum shape of radiofrequency rise time curve.

found that if the accelerating radiofrequency voltage was applied as shown in Fig. 5, rather than with a

[1] The accurate expressions are complicated by the effect of the straight sections of which these expressions take no account.

linear rise or an abrupt step, the beam was increased by 75 percent. There was also an increase of about 100 percent if the voltage on the inflector electrode was removed immediately after injection.

The largest beam with the bevatron aperture set at 6 in. $\times$ 18 in. was 3.5×10^{-11} coulombs per pulse (or about 2×10^8 protons per pulse). The injected beam measured at the end of the inflector electrodes was 10^{-8} coulombs. The over-all particle efficiency of the machine then was about $\frac{1}{3}$ percent. In the full-scale bevatron the losses due to gas scattering should be negligible because of the higher injection energy. In addition, while the tank height is scaled up by a factor of four the size of the inflector electrodes need not go up at all, so that ions will have a greater chance of missing the inflector after injection. It is therefore reasonable to expect a particle efficiency of at least several percent in the full-scale bevatron.

The bevatron development at the Radiation Laboratory is sponsored by the Atomic Energy Commission. It is under the direction of E. O. Lawrence and involves the work of many people. W. M. Brobeck is responsible for the basic design. Major responsibilities are also carried by those listed as authors in references *4, 5, 8,* and *9.* R. S. Shankland, of the Case Institute, and F. H. Schmidt, of the University of Washington, carried out some of the experimental measurements on the ¼-scale model.

References

1. Brobeck, W. M. *Rev. sci. Instr.*, 1948, **19**, 545.
2. Crane, H. R. *Phys. Rev.*, 1946, **69**, 542.
3. Gooden, J. S., Jensen, H. H., and Symonds, J. L. *Proc. phys. Soc.*, 1947, **59**, 677.
4. Kerns, Q. A. *et al. Bull. Amer. phys. Soc.*, 1949, **24**, 8.
5. Lofgren, E. *et al. Bull. Amer. phys. Soc.*, 1949, **24**, 8.
6. McMillan, E. M. *Phys. Rev.*, 1945, **68**, 143.
7. Oliphant, M. L., Gooden, J. S., and Hide, G. S. *Proc. phys. Soc.*, 1947, **59**, 666.
8. Sewell, D. C. *et al. Bull. Amer. phys. Soc.*, 1949, **24**,
9. Smith, Lloyd, Garren, A. A., and Henrich, L. R. *Bull. Amer. phys. Soc.*, 1949, **24**, 8.
10. Twiss, R. Q. and Frank, N. H. *Rev. sci. Instr.*, 1949. **20**, 1.
11. Veksler, V. *J. Phys. U.S.S.R.*, 1945, **9**, 153.

The Comparative Biochemistry of Vitamin Function

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PLANNED STUDIES of comparative biochemistry and comparative physiology are few as compared with the voluminous data on comparative morphology. The trend of recent years in the biological sciences away from the descriptive and toward the functional viewpoint, however, has evoked increased interest and study of the comparative approach. This has for the most part centered around the more gross aspects of nutrition and metabolism. Simultaneously, there has been an increased appreciation of the values to be gained from the study of some particular functional entity throughout a range of species, such that comparative biochemistry may well dominate the next developmental phase of biological science.

The history of the discovery of vitamins and elucidation of the vitamin concept has drawn heavily upon interspecies relationships. Williams' (*6*) discovery in 1919 that the antiberiberi substance was probably identical with a microbiological growth factor opened up a point of view that has permitted rapid exploitation of the vitamin field. Parallel studies in highly dissimilar species have characterized much of the work with the B vitamins from their discovery until the very present (*3, 4*), and indeed this group is characterized by the ubiquitous biological nature of its occurrence (*11*). Consequently, there exists in the literature a large amount of data of such a nature as to render much of it suitable for examination from the comparative approach. It therefore seems timely to consider what principles may be derived from a consideration of these data.

Chemical structure, natural distribution, and physiological activity of the vitamins. A variety of factors tends to strengthen the validity of grouping the vitamins into three categories: the B vitamins, the fat-soluble vitamins, and vitamin C.

The B vitamins are characterized by a ubiquitous biological distribution, and have a wide variety of structures. Naturally occurring analogues essentially involve modifications only in functional groups. Other vitamins, are not ubiquitous, and if vitamin C is ex-