The Case For New Accelerators

GeV by GeV, particle physics marches on. Improved equipment is the crucial factor in progress.

by Dietrick E. Thomsen

As soon as particle physicists start working with a new accelerator, they begin to plan an even bigger and better one. This process has been going on for 40 years at least, and it has brought us from E. O. Lawrence's first cyclotron, which was a comfortable tabletop operation, to the Fermi National Accelerator Laboratory, which swallowed up a whole village.

It would not be surprising if some members of the public began to look upon the particle physicists as if they were children who are never satisfied with their toys: As soon as they start to play with one, they want something else that they see in the shop window. Physicists are concerned to show that this continual escalation is not just an intellectual arms race, but is justified by the basic needs of the science. Victor F. Weisskopf of the Massachusetts Institute of Technology, who has been involved in these doings since their earliest days and once directed one of particle physics' main laboratories, is one of those who pleads the case. He spoke on the subject recently at the 1975 Particle Accelerator Conference in Washington.

Weisskopf presents a scientific justification for new accelerators. He does not concern himself with their priority in relation to other national and international needs so his words are unlikely to convert those who believe society can get along without an understanding of the fundamental structure of matter. For those who concede that point, the program of the particle physicists must still be justified: Is it the best way to move toward that end?

Weisskopf reminds us that every advance in accelerator technology has provided "access to new territory." Each step has uncovered new phenomena new particles, new activities among them. Some of these discoveries were expected, some not. Forty years ago there were three elementary particles, the proton, the neutron and the electron; today more than 100 entities are given that name. Forty years ago the interactions and force relationships were not too well understood, but believed to be simple; today they are not well understood but are known to be wonderfully complex.


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Weisskopf: Discovering new continents.

All these complications have been uncovered by improvements in instrumental technique. That is not simply a fortuitous historical procession, in Weisskopf's view, but intrinsic to the current state of the science. "It is still in the exploratory stage, not yet in the explanatory stage."

In view of that, Weisskopf finds it strange that theorists dominate the field: "Instrument builders are not mentioned on title pages." That is not to say that theorists have not been ingenious in supplying theories, but they have stuck very close to the phenomena and have often had to revise their ideas. There are more elegant ways to do theoretical physics, and Weisskopf, a theorist himself, is not much impressed with the profundity of the insights that have been achieved.

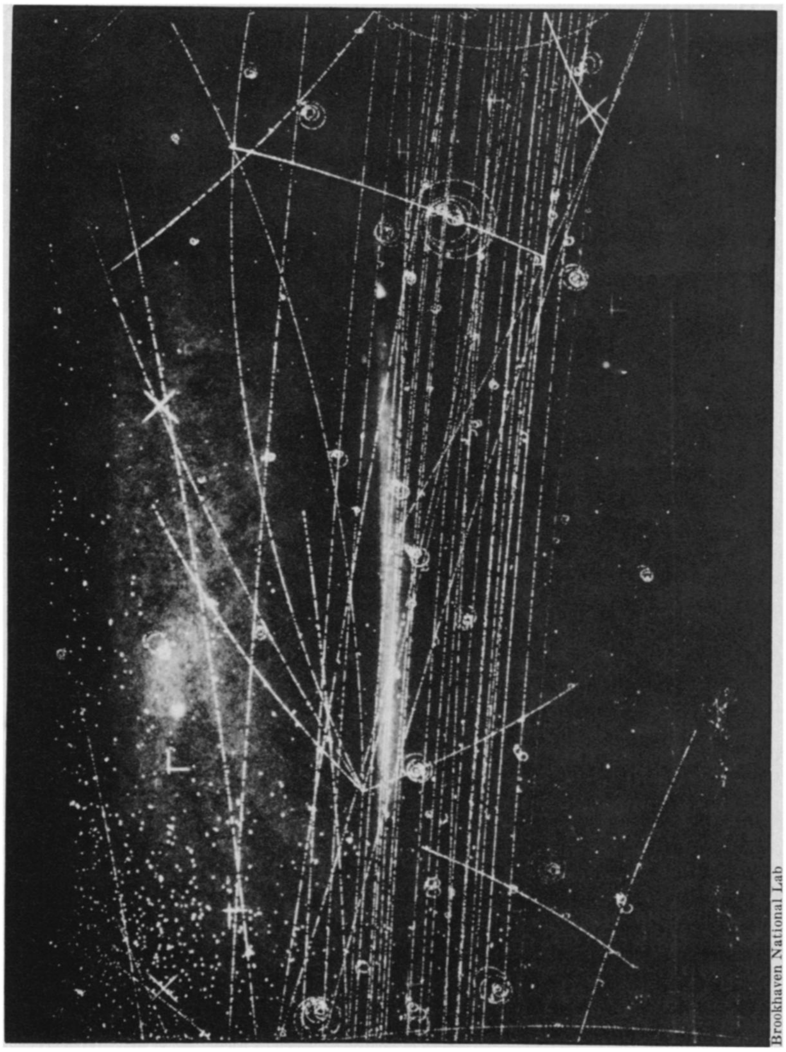
He draws an analogy to the voyage of Columbus. The instrument builders, he says, are like Columbus and the captains who planned and executed the voyage. The experimenters are like the people who jumped off the boats and proceeded to explore the terrain of the new continent. The theorists, however, are "the fellows who stayed in Madrid and predicted that Columbus would land in India." He insists that he tells this story not only at conventions of accelerator builders but also at meetings of theorists.

Nevertheless there is a state of the art, and it leads to certain expectations for the future. Weisskopf proceeds to review it, saying, "I hate to seem too tentative and vague."

Rather than start with the particles themselves let us begin with the interactions, the means by which particles influence each others' actions and existence and outline the differences that Weisskopf mentions between the situation before World War II and the situation now. ("Interaction" is the more fundamental term preferred by physicists. Forces are important consequences of interactions, and the two terms are sometimes treated as interchangeable, but there are things in interactions that are a little hard to describe by the textbook definition of force, "a push or a pull.")

Before the war three classes of interaction were known as far as practical particle physics is concerned, the strong, the electromagnetic and the weak. No additional interactions have definitely been discovered since then, but after 40 years of physics, as Weisskopf puts it, "the picture opens up," namely the functions of two of them have altered. In the 1930's the weak interaction was known as the governor of nuclear beta decay; today it is known to be involved in a variety of processes. Then, too, the strong interaction manifested itself mainly as the binding force of the atomic nucleus; its most important extension in present-day physics in Weisskopf's view is that it seems to be fundamentally involved in the internal structure of one class of particles (the hadrons), holding their internal constituents together.

Each interaction is outfitted with a field quantum, a particle (or particles) that serves to carry its influence from place to place. For electromagnetism this is the well-known photon; for the



Antimatter was the new continent of billion-volt physics. This is proton-anti-proton annihilation.

Brookhaven National Lab

weak interaction, three as yet undiscovered intermediate vector bosons; for the strong interaction (in its internal structure manifestation), a newly hypothesized particle, the gluon (the derivation of the name should be obvious).

Each interaction influences only certain particles, those that possess the particular characteristic to which it "couples." Thus only particles that have electric charge are influenced by the electromagnetic interaction. For the weak interaction the analogue is called weak charge, and for the strong interaction it is possibly a characteristic called color.

The particles that are not field quanta fall into two general classes, the hadrons and the leptons. Hadrons respond to the strong interaction; leptons do not. (The weak interaction and electromagnetism operate on some members of both classes.)

Hadrons are complicated entities. They appear to have an internal structure constituted by subparticles that theorists call quarks. The leptons are by comparison simple. They appear to be unstructured, and so far as anyone knows, there are only four of them.

Perhaps the fundamental entities in all this are the quarks and the leptons. One important difference between the two must be stressed: A free quark has never been seen; free leptons are abundantly seen. (Weisskopf proposes a possible reason for the difference.) But taking quarks and leptons together Weisskopf finds that he can set up a four-by-four pattern, a fourness that he is audacious enough to suggest may be a fundamental natural characteristic.

The pattern depends on two properties of the particles, color, which we have mentioned before, and what Weisskopf calls "flavor." Quarks come in three colors and four flavors; leptons in no color and four flavors. The flavors are up, down, strange and charmed. (Up and down refer to two orientations of isotopic spin, which, with strangeness and charm are some of the characteristics that theorists have had to invent for particles in order to explain why certain creations and annihilations take place and others do not, SN: 1/25/75, p. 58.)

Color in this context is meaningless in the water-paint sense. Still, it bears an analogy to the three primary colors of color-perception theory. If you mix the three primary colors you get white; if you add the three colors of the quarks, you get zero color. And a curious fact emerges from that. It turns out that all the systems we can see as free entities have zero total color, the leptons because they have intrinsically no color, the hadrons because all the schemes for making them out of quarks add up to zero total color. Thus it may be that "only colorless entities can be observed."

Also, if color is the source of the strong interaction—and that is still a hypothesis—there is an immediate explanation for the leptons' lack of strong interactions: They are intrinsically without color. An obvious conclusion, then, "Theorists are always very conservative people."

The original quark theory had only three flavors. There are several reasons for adding a fourth, and to these Weisskopf adds the observation that if leptons come in four flavors, why not quarks? Perhaps fourness is a basic pattern of nature. In this Weisskopf admits, "I stick my neck out." If someone finds new, heavier leptons—and there are theorists with reasons for wanting to find them—this pattern would go out the window.

Such an occurrence would be another example of theory responding to phenomena. The patterns that Weisskopf lays out, "theoretical hopes" as he calls them, are an attempt to arrange the phenomena that the equipment of particle physics has discovered. They point toward future work in two main directions: Gluodynamics and the unification theories.

Gluodynamics is the study of the strong interaction primarily within the structure of hadrons. Already results of experiments that probe hadron structure indicate some strange goings-on. Basically at short distances—that is, inside hadrons—the strong interaction seems to go soft. Its strength goes down. Why? And what does it have to do with the rest of particle physics?

The unification schemes, the unified field theories, have been much in the news lately (SN: 5/25/74, p. 340). They begin as attempts to unify the weak and electromagnetic interactions, to show them as different aspects of the same thing. And some go on to try to include the strong interaction. (Physicists have a general compulsion to formulate the most comprehensive theories they can. One does not ask why they seek unified field theories; the proper question would be why they did not.) Weisskopf points out that the electromagnetic-weak unification provides a formula by which one can estimate the mass of the intermediate vector bosons, the carrier particles of the weak interaction. It comes to about 50 billion electron-volts, many times the mass of any known particle. That mass, Weisskopf notes, by the way, gives an insight into why the weak interaction is so

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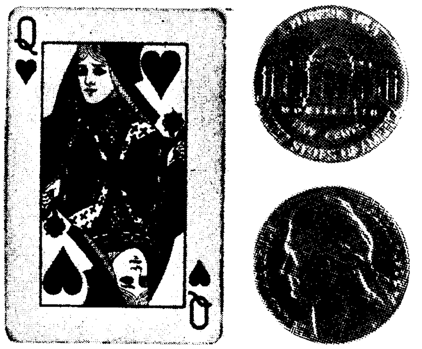
formations of the underlying probability space that preserve the probability measure. Among these so-called measure-preserving transformations are some, called Bernoulli shifts (after the famous 18th-century father of modern probability, Daniel Bernoulli) that are derived directly from roulette wheel models. The repeated spins of a roulette wheel may be represented by a string of symbols (stretching to infinity in both directions) each of which denote the outcome of a particular spin. The Bernoulli shift is the transformation that consists of translating (that is, shifting) this string of symbols one position to the right. Such a shift corresponds to a time translation of one unit.

Bernoulli shifts are the transformations in ergodic theory that correspond exactly to the independent processes of probability theory: The roulette wheel is the device that carries this correspondence. Bernoulli shifts arise in a variety of contexts, from multistep Markov processes to the Brownian motion of a hard-sphere gas. The fundamental question concerning the isomorphisms of the roulette process translate directly to an equivalent question concerning the isomorphisms of Bernoulli shifts. And this question has been recently settled by Stanford mathematician Donald Ornstein.



Ornstein has shown that Kolmogorov's entropy invariant provides a complete classification for Bernoulli shifts. Specifically, he proved that any two Bernoulli shifts with the same entropy are isomorphic. In other words, the information content of an independent process completely determines its probabilistic structure, except possibly for events with probability zero. Ornstein's result thus provides some insight into the epistemological status of random processes: Their random nature is uniquely determined by the information content (entropy) of their structure. Of course his theorem did much more than this on a technical level: It provided a simple and direct means of deciding whether two Bernoulli shifts (hence, any two independent random processes) are essentially the same.

Ornstein's work, which he has drawn together in a monograph, "Ergodic Theory, Randomness and Dynamical Systems," recently published by Yale University, leads to further insights into the nature of nondeterministic processes. Many such processes may be derived directly from Bernoulli shifts. These processes, called Bernoulli processes, are exactly those that can be approximated by finite coding of a roulette wheel—the longer the code, the better the approximation. They are in some sense the most random possible processes, and they are the only random processes that can be approximated well by a mechanism with a finite memory.

Ornstein and others have shown that any gross measurement—one with only a finite number of possible outcomes—on a mechanical system is a Bernoulli process: It produces a result essentially indistinguishable from a finite coding of a roulette wheel or a multistep Markov process. This result provides yet another clue concerning the relation between deterministic and nondeterministic phenomena: Gross measurement on a completely deterministic system yields the most random possible process!

A common desideratum of any random process is that behavior in the distant past should have little or no influence on the probabilities of present behavior. Kolmogorov proposed this as a criterion for completely nondeterministic processes. Specifically, he studied a class of processes, since called Kolmogorov processes, that satisfy the so-called "zero-one" law of probability theory: If knowledge of what the process did in the very distant past can help in any way to predict the present probability of a particular event, then that event must either have probability zero or one. A mechanical system has this property if and only if the only deterministic measurements that can be made on the system are those whose results are already certain in advance of the measurement. Every Bernoulli process is a Kolmogorov process, and Kolmogorov believed that the converse was also true, namely, every process that satisfies the zero-one law must have as its basic stochastic mechanism an independent process such as a roulette wheel.

Ornstein showed that this conjecture is false: He constructed an example of a completely nondeterministic process (that is, a process satisfying the zero-one law) that cannot be approximated by any multistep Markov process or by any finite coding of roulette wheels. This yields a third major insight into the nature of random processes: It is simply not true that all nondeterministic processes arise from a roulette-type mechanism. ☐

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much weaker than the electromagnetic if they are two aspects of the same thing. The mass of the boson reduces the strength of the weak interaction compared to the electromagnetic, whose carrier particle has zero mass.

In conclusion Weisskopf lists the next desirable steps in equipment and what they may hope to find in the light of these theoretical patterns.

First he proposes very high energy colliding beams of electrons and positrons (a positron is the antiparticle to an electron). The matter-antimatter annihilation that occurs when electron and positron meet produces a virtual photon, which then can turn itself into other particles. Such a collision, especially the production of what is called a timelike virtual photon, is a way of concentrating a large amount of energy into a small space. It is a good way of creating hadrons and studying their structure and of making previously unknown particles, as has lately been in the news. (SN: 11/23/74, p. 324) Because electron and positron have both electromagnetic and weak interactions, their collisions are also a good way to probe the unified theories.

A proton accelerator or proton-proton colliding beams that gave 100 billion electron-volts "in the center of mass"—thus made that much energy available for creation of new particles—could discover the intermediate vector bosons. It should be able to monitor high energy, and therefore short distance behavior of the strong interaction to see whether it really does go down. It might find free quarks if they can exist, and it might find exotic new particles. "If not," says Weisskopf, "the whole house of cards I have tried to build will collapse."

A fixed-target accelerator more energetic than the biggest now in existence could provide beams of secondary particles (neutrinos, pi mesons, K mesons, muons) with more than 200 billion electron-volts energy. These could test the unification of the weak and electromagnetic interactions, especially whether their strengths become equal in experiments where large amounts of momentum (comparable to the mass of an intermediate vector boson) are transferred from one particle to another. They could also test whether the strong interaction gets weak at high energies.

Weisskopf warns us to expect the unexpected—a good motto in particle physics. The theoretical patterns, ingenious though they are, are subject to correction by the phenomena, and they have a long history of that. "Very probably," he predicts, "all these ideas will turn out to be landing in India. People will discover a new continent, and this will be basic for our understanding of the structure of the universe." ☐