The Upsilon Particle

Its unexpected discovery as the heaviest particle has prompted physicists to introduce a massive new quark, raising the number of these unobserved elementary subparticles from four to five

by Leon M. Lederman

The search for the ultimate, indivisible constituents of matter that began with the pre-Socratic, atomistic natural philosophers continues unabated after 2,400 years. In the past few decades the number of identified subatomic particles has risen to more than 100, as powerful machines were developed for smashing bits of matter together and studying the scattered by-products. At first physicists believed these particles could not be broken down into smaller entities. Then they found that only the four leptons (the electron, the muon and two kinds of neutrino) seemed to be truly elementary in the sense of having no measurable size and no constituent parts. The rest of the particles, the hadrons (including the proton, the neutron and the pion), turned out to be complex objects that showed signs of an inner structure. In 1964 the quark hypothesis, which has been a cornerstone of particle physics ever since, was introduced as a description of that structure. It held that the hadrons were all ensembles of only three elementary entities named quarks. An additional quark was soon postulated, for both theoretical and experimental reasons. Although none of the four quarks has ever been observed, in spite of many attempts to isolate one, there are good grounds for believing they exist.

Last year a group of investigators (of whom I was one) from Columbia University, the State University of New York at Stony Brook and the Fermi National Accelerator Laboratory (Fermilab) discovered a new particle with a mass whose energy equivalent is 9.4 GeV (billion electron volts), a mass more than three times greater than that of any subatomic entity previously identified. Designated upsilon (Υ), the new particle points to the existence of a fifth quark, one more massive than any of the others. Since the original four quarks could account for all the known properties of hadrons, a fifth subparticle seems superfluous. Its existence appears to be a mixed blessing for the quark hypothesis. On the one hand it should help physicists to determine the nature of the hitherto inscrutable quark forces. On the other the very proliferation of quarks could topple the central hypothesis that they are the most fundamental constituents of matter. After all, quarks were first introduced to account for the ever increasing number of hadrons. Now it is the quarks that are growing in number, and there seems to be no theoretical reason that would block the discovery of even more massive ones.

The research that led to the discovery of the upsilon began in 1967 at the Brookhaven National Laboratory. With the 30-GeV Brookhaven synchrotron we fired energetic protons (p) at uranium nuclei consisting of neutrons and protons, collectively known as nucleons (N). We wanted to study what happened when a pair of oppositely charged leptons (l^- and l^+) emerged, a reaction that can be written $p + N \rightarrow l^- + l^+ +$ anything. "Anything" means we had no interest in the other particles produced. Before I describe our experiments let me provide somewhat more background on leptons so that the reader will better understand why we worked so intensively with them for 10 years.

Leptons are distinguished from other subatomic particles in that they are not subject to the "strong" force that binds protons and neutrons together to form atomic nuclei. As a result energetic leptons have great power to penetrate matter. The neutrino (ν), for one, has no electric charge and could pass through millions of miles of lead without colliding with anything. The muon (μ), which weighs 200 times more than the electron (e^-) but otherwise exhibits identical properties, is slowed when it moves through matter by the burden of having to drag its electric charge through other electric charges. Nevertheless, because such electromagnetic forces are 100 times weaker than the strong force, the muon could penetrate many meters of iron. With a charge identical with the muon's, the electron is stopped more easily because of its smaller mass; it cannot plow its way through iron as the heavier leptons can.

The lepton pair ($l^- + l^+$) created in the reaction at Brookhaven had the same quantum properties as the quantum of electromagnetic energy: the photon (γ). This was apparent from the ease with which a photon changes into either a muon pair ($\mu^- + \mu^+$) or an electron-positron pair ($e^- + e^+$), illustrated by the reactions $\gamma \rightarrow \mu^- + \mu^+$ and $\gamma \rightarrow e^- + e^+$.

A major difference between photons and lepton pairs is mass. Whereas the lepton pair has a positive rest mass when it is regarded as a single particle moving with a velocity equal to the vector sum of the motions of its two components, a photon always has zero rest mass. This difference can be glossed over, however, by treating the lepton pair as the offspring of the decay of a short-lived photonlike parent called a virtual photon. The concept of the virtual photon also appears in other reactions where the electric and magnetic properties of matter are being examined. The laws of the conservation of energy and of momentum enabled us to routinely compute the mass, energy and momentum of the virtual parent, in spite of its evanescent nature. To determine its mass (M) we had only to measure the energy of the l^- and l^+ particles emerging from the collision. The formula $M^2 = 4E^-E^+(\sin^2\theta)$ told us that we were dealing with a massive parent whenever both the angle (θ) between the leptons and the prod-

EDITOR'S NOTE

The author wishes to acknowledge the contribution to the work described in this article made by the following individuals: J. A. Appel, B. C. Brown, C. N. Brown, J. H. Christenson, S. W. Herb, G. S. Hicks, D. C. Hom, W. R. Innes, A. S. Ito, H. Jöstlein, D. M. Kaplan, R. D. Kephart, P. J. Limon, B. G. Pope, J. C. Sens, H. D. Snyder, K. Ueno, T. Yamanouchi, J. K. Yoh and E. Zavattini.

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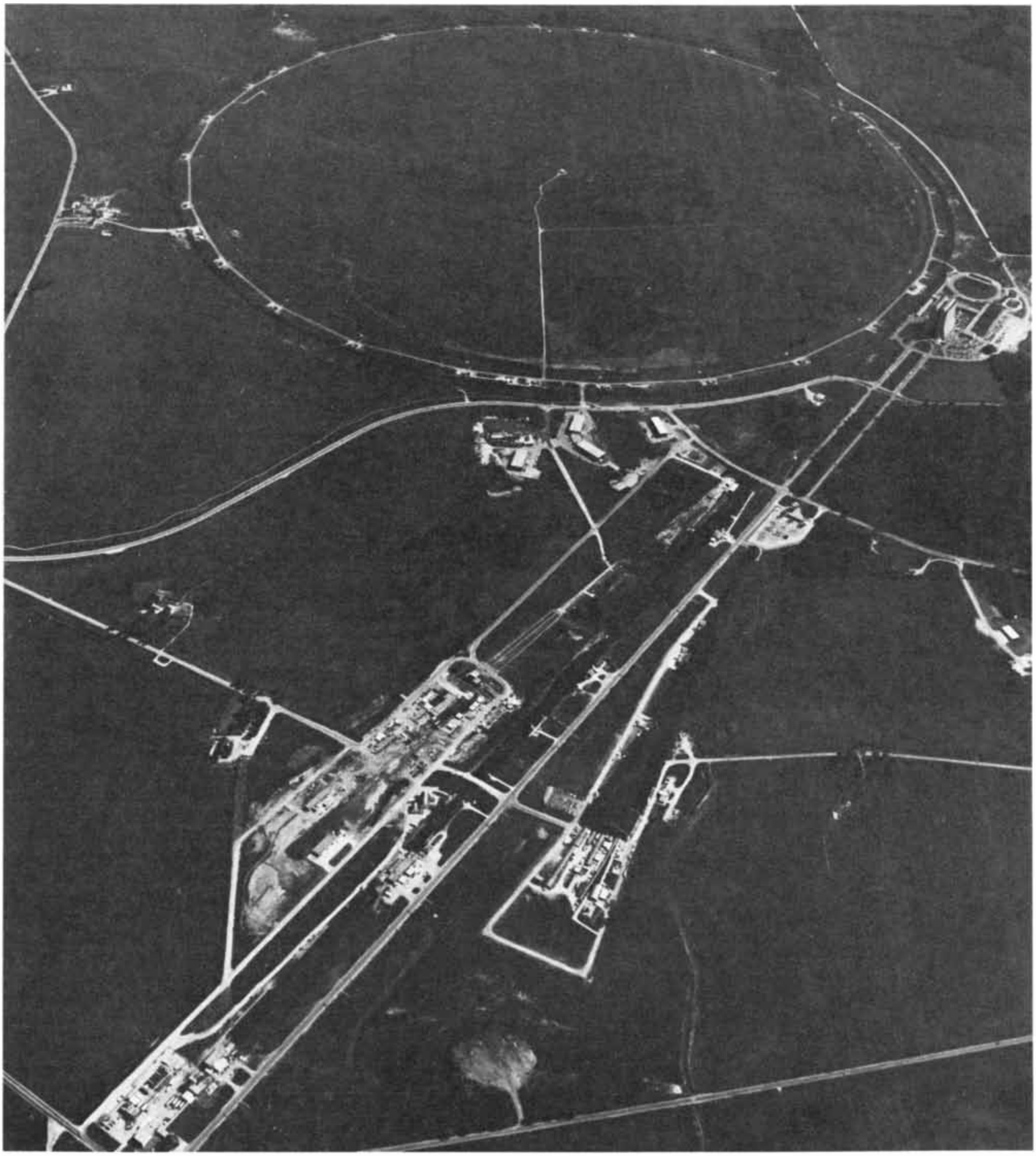
uct of their respective energies (E^-E^+) were large.

As long ago as 1967 we recognized in a vague and intuitive way that the emission of virtual photons could be indicative of unexplored domains inside the colliding nuclear particles. We reasoned that when an extremely energetic proton collided with a target nucleon, a highly excited and complex state would be generated. Most of the time this state would lose energy with the emission of such strongly interacting particles as pions and kaons. Occasionally, however, deexcitation would result in part from the emanation of virtual photons that would decay immediately into lepton pairs.

We had expected the masses of the virtual particles, as computed from measurements made on the leptons, to



PROTON SYNCHROTRON at Fermi National Accelerator Laboratory (Fermilab) was used to generate muon pairs in experiments that led to the discovery of the upsilon particle. Here the 400-GeV (billion-electron-volt) machine appears as the large circle, which has a circumference of four miles. Tangent to the circle are long tunnels that carry particles to experimental stations. The upsilon work was done in the proton laboratory, which is in the large area at the lower left that looks as if it is under construction. Fermilab stands on a four-by-five-mile tract 30 miles southwest of Chicago in Batavia, Ill. Built by the Atomic Energy Commission under contract with a consortium of 53 universities, the laboratory facilities are used by groups from all over the world. Under the direction of Robert R. Wilson the accelerator, which went into full operation at 200 GeV in 1972, was upgraded to 300 GeV in 1973 and to 400 GeV in 1974.

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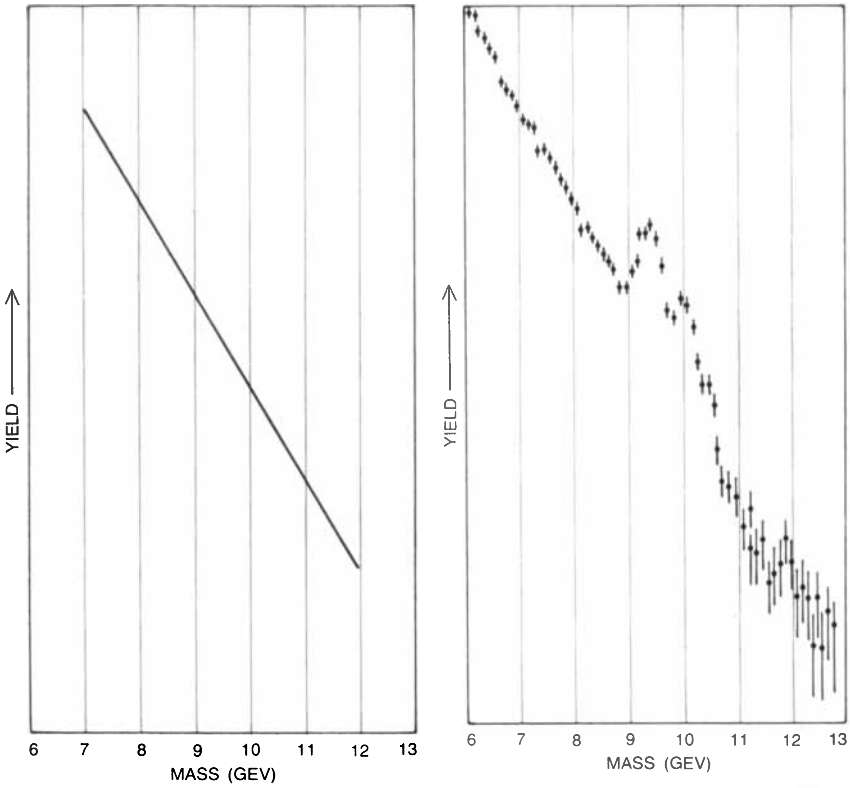
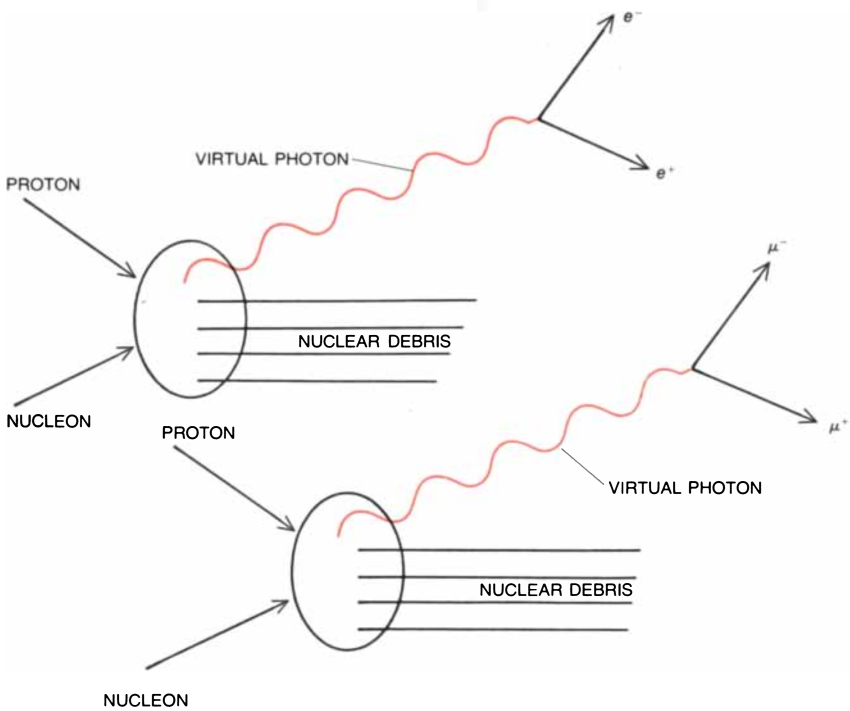


MASSES OF VIRTUAL PHOTONS that decayed into muon pairs were expected to be distributed continuously (*left*). This turned out to be the case, although in addition there was an unexpected cluster at about 9.4 GeV (*right*). Such a cluster, called a resonance, marked the presence of the upsilon. Vertical error bars through each data point represent the uncertainty as to where it should be plotted. The smaller the number of events, the larger the uncertainty.



COLLISIONS BETWEEN PROTONS AND NUCLEONS (either protons or neutrons) sometimes generate virtual photons that decay immediately into electron-positron pairs (e^-e^+) or into pairs of oppositely charged muons ($\mu^-\mu^+$). The bottom reaction will require much more energy than the top reaction because the muon is 200 times more massive than the electron. The additional mass of the muon, however, will enable it to penetrate much deeper into matter. The nuclear debris from these particular reactions will have very little penetrating power.

be distributed continuously [*see top illustration at left*]. Because we had recognized that smaller masses would be easier to create than larger ones, we thought that the yield of virtual photons would fall steeply as their mass increased. Although we did not expect the mass calculations to cluster around any particular value, we hoped this would happen. Such a cluster is called a resonance. If a resonance did manifest itself, it would indicate that the lepton pairs emanated not from some virtual entity but from some real particle. On the basis of Werner Heisenberg's uncertainty principle we could then estimate the size of whatever material within the colliding nucleons had served as the source of the new particle. Heisenberg's principle suggests that the greater the particle's mass, the smaller the size of its source. This meant that if we discovered sufficiently massive resonances, we would in fact be detecting extremely small structures within the target nucleons.

Our search for such lumps within the target nucleons was undertaken in 1967 in spite of the widespread view that matter in highly excited states was smooth and homogeneous. Moreover, even if such small but massive entities did exist, our equipment might not be sensitive enough to detect them. Other experimenters had already discovered that low-mass resonances were extremely rare; in the Brookhaven accelerator a lepton pair with a mass close to that of a proton would be created only once in a million collisions. Larger masses would be produced even less frequently, and for every one produced millions of strongly interacting particles would also be produced. Our detector would have to be capable of sorting out the rare lepton pairs from the abundant background hadrons.

After much discussion we realized we could build a detection system based on the fundamental fact that leptons can penetrate matter and hadrons cannot. Since muons can travel deeper into matter than electrons, we decided to concentrate on them and to ignore any electron-positron pairs also created. That led us to put 10 or more feet of iron between the uranium target and the lepton-pair detector. The iron would absorb the strongly interacting particles but allow the muons to pass through and trip a series of scintillation counters.

The drawback of this detection system was that it would alter the trajectories of the muon pairs. The atoms of the iron not only would decelerate the muons, causing them to lose energy, but also would push and pull on their electric charge, deflecting them from their original paths. We were therefore in a predicament. If we measured the energy and the angle of separation of the muons after they emerged from the iron absorber and used these values to calcu-

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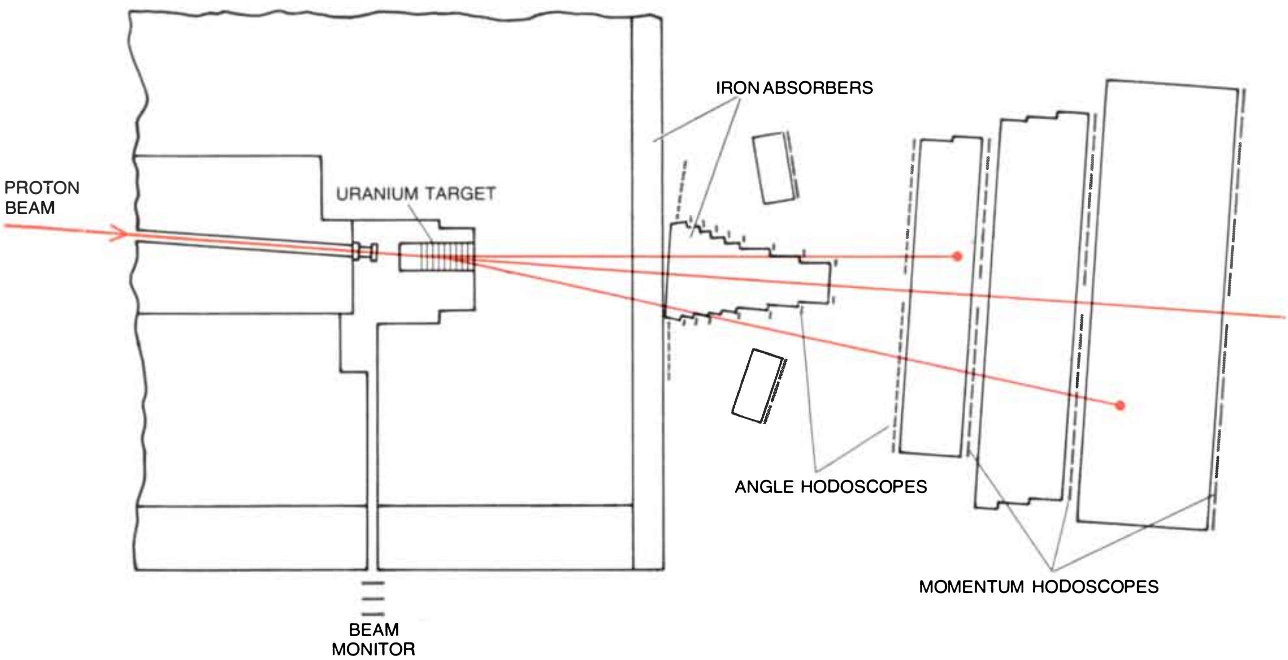
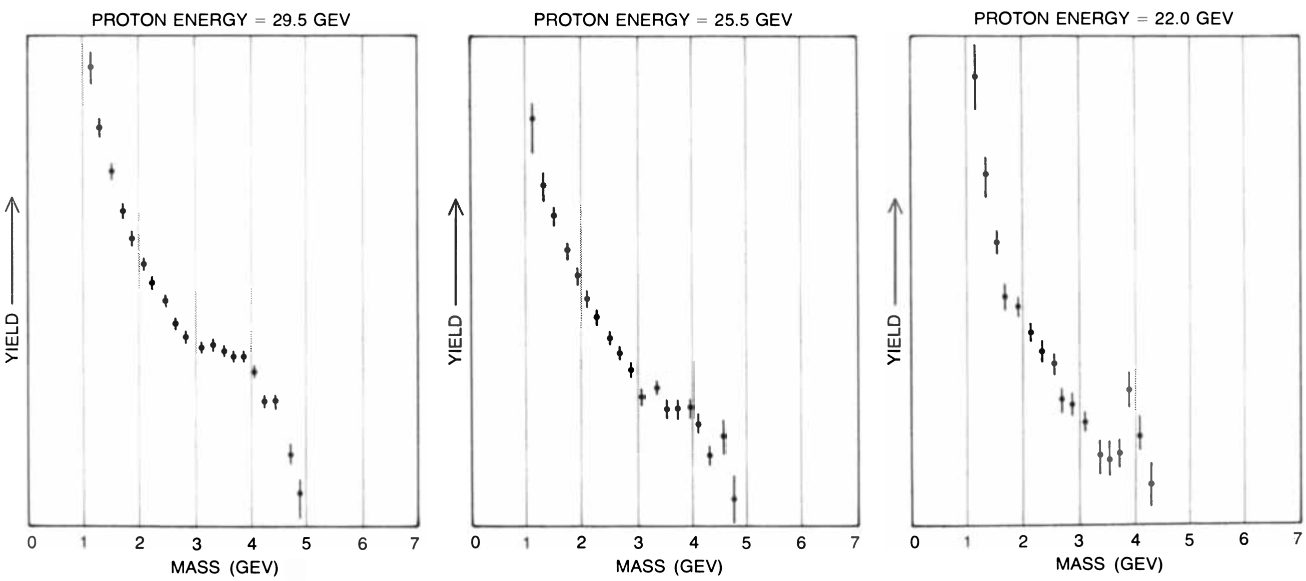


APPARATUS AT 30-GEV ACCELERATOR of Brookhaven National Laboratory generated muon pairs when protons struck uranium. The muons passed through iron that absorbed unwanted nuclear debris. Hodoscopes measured the muons' angles and momentum.

late the mass of their virtual parent, we would get an inaccurate answer. Yet we could not make a more accurate calculation by looking at the muons before they entered the absorber because at that point the enormous flux of hadrons would interfere with the counters. At this early stage in our work we were not too concerned about having to settle for an imprecise calculation. The goal was to detect heretofore unseen resonances at high masses, and we believed our apparatus would do this even though it would also distort the characteristics of such resonances. That would be a small price to pay if we could discover a new particle.

We began collecting data in the fall of 1968. A digital computer processed the information and drew a graph of the yield of muon pairs observed at each mass. Since we were studying an unexplored reaction, we had no idea what the distribution would look like. Nevertheless, we were startled by the drop that began at about 1.5 GeV, flattened out just above 3 GeV and then plunged precipitously at the upper limit of our detection system, where we were not able to collect much data [*see illustration below*]. This "shoulder" excited us. We wondered if it could represent a sharp resonance that was smeared by our crude apparatus but marked the presence of some new particle. When we lowered the energy of the bombarding protons, the shoulder would not go away. That was a good sign. It meant that the curious distribution was probably not the spurious result of some undetected quirk in the equipment. The



UNEXPECTED "SHOULDER" in the masses of the virtual photons generated at Brookhaven would not go away when the energy of the bombarding protons was lowered from 29.5 GeV (*left*) to 25.5 GeV (*middle*) and then to 22.0 GeV (*right*). This result suggested that the shoulder was real, perhaps the poorly resolved resonance of a new particle and not the counterfeit product of apparatus malfunction.

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burden of proof, however, was still on us. We could not completely dismiss the possibility that the distortion effects of the apparatus might be so overwhelming that they had spuriously warped the low-energy distribution as well. Moreover, we had to consider the possibility that the shoulder might be a peculiar characteristic of the smooth distribution of virtual photons rather than the smeared resonance of a new particle.

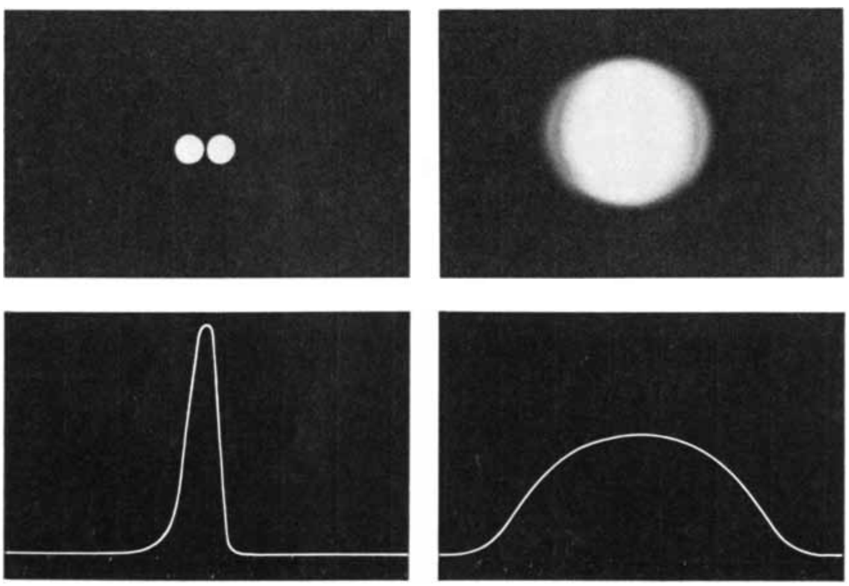
Tentative as our uninterpreted results were, theoreticians took an immediate interest in them because they seemed to relate to the quark hypothesis. The original hypothesis of 1964 suggested that all known hadrons were composed of three quarks, labeled *u, d* and *s* (for "up," "down" and "strange"), and three corresponding antiquarks, $\bar{u}$, $\bar{d}$ and $\bar{s}$. Although the original quark model beautifully and simply accounted for the static properties of the more than 100 hadrons, it did not describe their dynamical properties. By 1968, however, pioneering workers had used the quark model to explain scattering data and collisional processes. The main difficulty with their explanation was its lack of uniqueness: reasonable alternative hypotheses that did not incorporate quarks could account for the dynamical characteristics just as well.

Our lepton-pair data turned out to provide a considerable boost to the quark explanation of hadron dynamics. In 1970 two Stanford University physicists, Sidney D. Drell and Tung-Mow Yan, tried to use a quark model to generate our lepton-pair results theoretically. Their predictions matched our data fairly well near 2 GeV but fell below them near 3 GeV. Encouraged by this partial correlation, by the intriguing possibility of clustering and by the tremendous interest of theorists in our results, we decided to run an improved version of our experiment on the more powerful accelerator at Fermilab. The accelerator's tremendous energy, which was at that time 300 GeV, would increase the probability of pair emission at 3 GeV, and we hoped this would finally enable us to identify the significance of the mysterious shoulder.

Then in 1974, before we began taking data, the three-quark model was overthrown by what was called "the November revolution." The discovery of a new particle was independently announced by Samuel C. C. Ting of Brookhaven and the Massachusetts Institute of Technology and by Burton D. Richter of Stanford. At Brookhaven the new particle, which was named by Ting *J* and by Richter ψ (psi), showed up as a spectacular enhancement in the masses of virtual photons that had decayed into electron-positron pairs [*see illustration on page 78*].

The discovery of the J/ψ resolved several significant problems in particle physics. It explained our lepton-pair data, and it suggested the existence of a fourth quark, designated *c* (for "charm," the new quantum-mechanical property it implied). The shoulder we had seen in 1968 was now interpreted as being a badly smeared version of the J/ψ's narrow enhancement at 3.1 GeV. The revolutionary aspects of the J/ψ lay in this very narrowness. According to Heisenberg's uncertainty principle, a narrow, or well-defined, mass implies a lifetime that is long compared with that of most other subatomic particles. And a long life span meant that the J/ψ was inhibited from decaying into such particles as pions and kaons. The existence of a fourth quark could explain why this was so. Since quarks are truly fundamental, one kind of quark cannot easily turn into another. If the J/ψ's were made up of only the charmed quarks, they could not easily decay into pions and kaons, which are made up of only the other three quarks. Subsequent investigations supported the interpretation of the J/ψ as a bound state of a fourth quark and its antiquark. The concept of a fourth, charmed quark was further confirmed when particles were discovered that seemed to consist of various combinations of all four quarks.

A comparison of our shoulder distribution of 1968 and the J/ψ data of 1974 bore out our conviction that what we had gained in sensitivity we had lost in resolution. We had detected more than 10,000 muon pairs with our highly sensitive apparatus, but we could not interpret the smeared distribution. The discoverers of the J/ψ at Brookhaven, on the other hand, used a new generation of particle detectors to find only 242 pairs, but because their apparatus could locate the positions of the pairs on the mass scale with greater accuracy they saw a highly resolved, narrow peak.



PROBLEM OF POOR RESOLUTION in high-energy experiments is illustrated by comparing photographs with curves of experimental results. An unfocused camera can make two lights (*top left*) appear to be one (*top right*). The Fermilab apparatus made the J/ψ particle's narrow resonance (*bottom left*) look broad (*bottom right*). A computer helped to clarify the distortion.

Now that the mystery of the shoulder had been solved, we decided to use the new Fermilab accelerator to look for resonances in the unexplored mass range above 5 GeV. In 1975 and 1976 we observed hundreds of events in three lepton-pair runs. The energy of the Fermilab accelerator had been boosted to 400 GeV, an increase that would turn out to be crucial for our work. This time we could monitor the distorting effects of our apparatus by examining how it altered the J/ψ resonance, which we could not have done in 1968. We also had years of experience with muon pairs and of progress in detector development that we could put to good use.

In February of last year our group began to assemble a new version of the lepton-pair experiment utilizing what we had learned over the preceding two years. We realized that in order to draw any conclusions about the rarer, higher masses we would have to observe many more events. At the same time we would have to improve the resolution or we would be confronted with the same kind of uninterpretable data we had collected in 1968.

John Yoh of Columbia had noticed a small number of events near 9.5 GeV in our 1976 results. He put a bottle of Moët champagne, labeled "9.5," in our group's refrigerator. This convinced no one that we were on the track of a new particle. We were nonetheless encouraged in our search by the fact that our data were unique: no one else had ever seen 350 lepton pairs with masses

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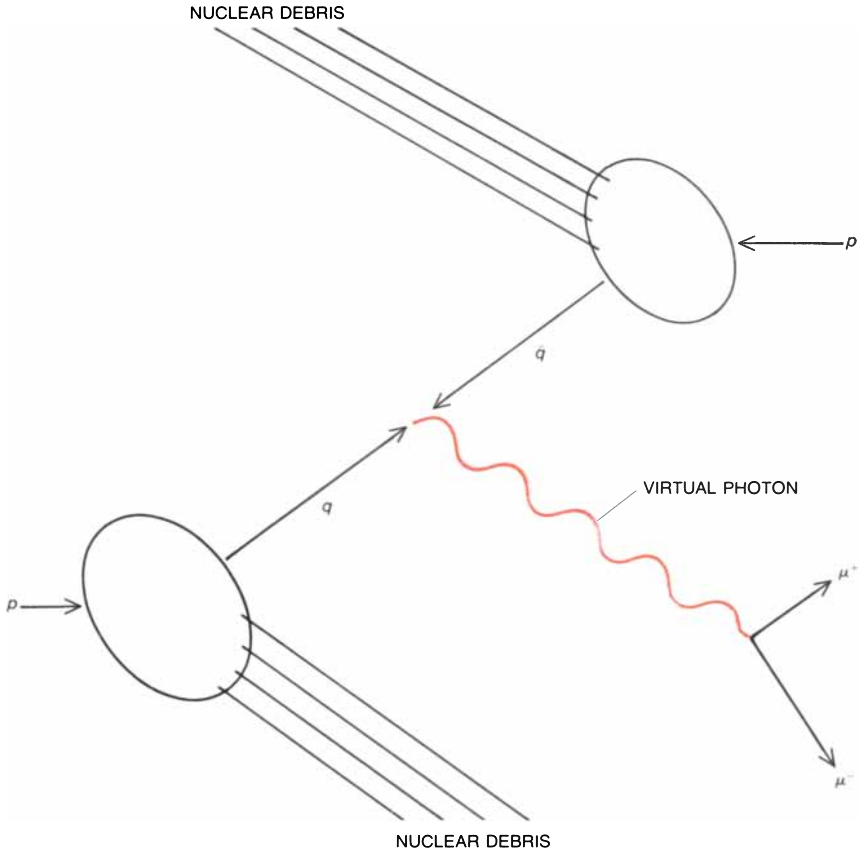
greater than 5 GeV. There might just be something there—somewhere.

Experience showed we could move the detectors closer to the target so that more muon pairs would reach them. Stephen W. Herb of Columbia had predicted correctly that this would not also increase the enormous flux of hadrons interfering with the detection system. In 1968 we had used iron to absorb the unwanted particles, but the iron atoms, with their 26 protons and 26 electrons, exerted an electromagnetic force on the muons that deflected them from their original paths. As a result the masses of the muons could not be accurately calculated. This time we would use the metal beryllium as the principal absorber. With only four protons and four electrons, the beryllium would hardly deflect the muon pairs, although it would still be able to screen out most of the hadrons.

One major obstacle remained. Muons are treacherous particles. As I have mentioned, they can easily penetrate many meters of iron. We needed absolute assurance that our muon pairs were honest: that they had been born in the target and had proceeded undeviated and unscattered through a large deflection magnet and into our counters. To gain this assurance we wanted to put a detector in the middle of the magnet. This proved difficult (it was somewhat like designing a delicate and precise watch to operate inside a blast furnace), but Walter R. Innes of Fermilab came up with a successful design. Still, we were not satisfied with the setup. The events of greatest interest were also the rarest ones. Over a long day with more than 10 billion nuclear collisions per second extremely improbable happenings could conspire to spoof the experiment. To guard against this possibility Charles N. Brown of Fermilab designed a simple magnetic system that would remeasure each muon's energy after it emerged from the main detector.

On May 1 of last year we gathered our first data. We were elated to find that our improved apparatus registered 90 times more muon pairs than it had the year before. The upgraded accelerator had functioned superbly, supplying unlimited quantities of protons with needle-sharp precision. In the first week we observed 3,000 muon pairs with energies higher than 5 GeV, more than 10 times the rest of the world's data and of much better quality. We graphed the results, and they seemed remarkably free of the interfering effects of hadrons. The J/ψ resonance showed up clearly, which meant we had succeeded in increasing the resolving power of our apparatus. Our excitement rose to a high pitch when we saw that the steady decrease in the yield of muon pairs, as they became more massive, was interrupted near 10 GeV by an intriguing bump.

The following week we doubled our data and still the bump remained. Although we could no longer dismiss it as a misleading happenstance, we wondered if it could be the wayward product of some undetected idiosyncrasy of our apparatus. Perhaps the deflecting magnets or the counters had malfunctioned. Fortunately we had mechanisms for checking that out. We looked separately at each square centimeter of the detector's surface to see how the muons that struck each area were distributed. Everywhere we found smooth distributions, indicating that the apparatus had not generated the resonance. Moreover, when we artificially mixed Monday's μ^+'s with Tuesday's μ^-'s to form fake $\mu^+\mu^-$ pairs, we got a perfectly smooth distribution that conformed to all our expectations about how the equipment worked. As the apparatus passed other tests and as we accumulated more data we became convinced that the resonance represented something real: a new particle with a mass of 10 GeV. Although we wanted to keep our results secret until we could fully interpret them, rumors of our discovery spread rapidly throughout the physics community. Therefore on June 20 we made our data public: 26,000 pairs, almost 100 times the data of all previous experiments combined. We named the particle upsilon.



QUARK MODEL, although introduced to explain the static properties of particles, can also account for such dynamical processes as the creation of muon pairs. Sidney D. Drell and Tung-Mow Yan of Stanford University proposed that a virtual photon that decays into a muon pair is formed when a quark (q) from the bombarding proton and an antiquark ($\bar{q}$) from a quark "sea" associated with the target nucleon annihilate each other. Drell and Yan tried to predict the Brookhaven data, succeeding fairly well at masses near 2 GeV but not with those near 3 GeV.

We next set out to determine the width of the resonance, using the same method by which the span of the J/ψ resonance had been calculated. In effect the width is the uncertainty in the mass of the resonance, and Heisenberg's principle associates a narrow peak (a small uncertainty) with a long lifetime, and a broad peak (a large uncertainty) with a short life span. After we had gathered more data we found that the resonance consisted of two closely spaced peaks (with a suggestion of a third) 600 MeV (million electron volts) apart and each peak 500 MeV wide. This indicated that the upsilon could exist in two and perhaps three states of slightly different energies. Before we concluded from these width values that the resonance of the upsilon was intrinsically narrow we needed to take into account the distortion effects of the inevitably imperfect apparatus. Apparatus with a low resolving power will make nature's peaks look broad, much as a camera lens of poor quality will blur the fine details in a photograph. In our Brookhaven experiment of 1968 poor resolu-

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tion had distorted the data to the point where they were uninterpretable.

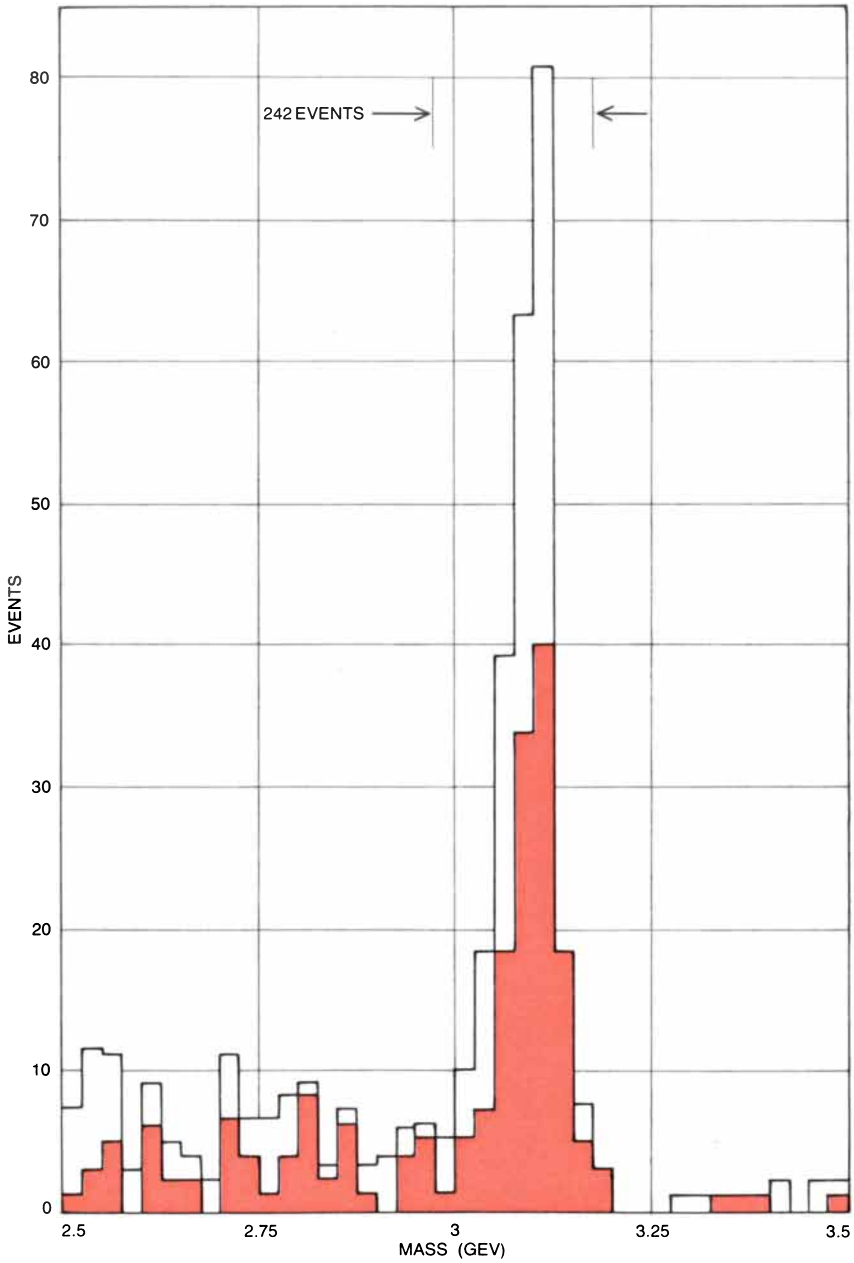
To determine how the Fermilab apparatus had deformed the shape of the resonance we relied on a game-theory approach in which a computer simulated our entire experiment. Such simulations, called the Monte Carlo method, are ubiquitous in high-energy physics. In our case the computer, programmed to know the location and function of each piece of our apparatus, selected a configuration of two muons and traced their trajectories to the final detector. If the computer program called for the muons to encounter an absorber consisting of, say, beryllium, the program would call for the muons to be scattered just as if the muons and the beryllium were real. The computer we used was a powerful one, so that the simulation could trace tens of thousands of muon pairs through the apparatus.

We then graphed the mass distribution of the Monte Carlo events and discovered that the simulated upsilon resonance was much narrower than the measured one. This suggested that the measured width was produced mainly by the apparatus. Complex computer programs do, however, have bugs. Had we caught them all? Perhaps the simulation was wrong and the resonance was actually as broad as the one we had measured. Fortunately we had ways of eliminating that possibility. Since we already knew how our apparatus had distorted configurations such as the J/ψ resonance, we could test the Monte Carlo program to see whether it correctly revealed such distortions. Indeed it did, and we confidently concluded that the width of the upsilon resonance was less than 100 MeV. This extremely narrow width indicated that our new particle had a very long lifetime.

One would normally expect that a particle with a mass as great as 10 times the mass of the proton should have an enormous number of lower mass states into which it could decay, each state contributing to a shorter lifetime. But contrary to expectations the upsilon, the heaviest particle ever discovered, has a long lifetime. This means that it does not decay into the less massive hadrons, all of which are composed of *u, d, s* and *c* quarks. At the time of our discovery last year, however, the known laws of physics could not explain why this was so. The conclusion was clear and exciting: some new law of physics forbids (or, more precisely, inhibits) the upsilon from decaying into ordinary hadrons.

In search of this new law we looked to see if any work in theoretical physics had anticipated our discovery of the upsilon. Over the years many theorists have suggested the existence of new particles to account for puzzling data, and we wondered if the upsilon could be one of those that had been proposed.

The only reasonable candidate was a new, massive quark bound to its antiquark in atomlike configurations that would show up as a closely spaced set of masses having many features of the upsilon. The theoretical papers that raised the possibility of such a quark were speculative discussions appealing to aesthetic prejudices. One group of papers hoped the existence of a new quark would be able to account for some curious results of certain neutrino-scattering experiments. Our best calculations, made early this year, indicate that the upsilon has resonances at 9.4, 10.0 and 10.4 GeV [*see top illustration on page 80*]. A particle made up of a fifth quark and its antiquark might exist in a ground state, or lowest state, at 9.4 GeV and in excited states at 10.0 and 10.4 GeV. Moreover, the existence of a fifth subparticle would neatly account for the long lifetime of the upsilon, just as the fourth quark had accounted for the long life span of the J/ψ. If the upsilon consisted only of the fifth kind of quark, it could not decay into ordinary hadrons, which consist of various combinations



J/ψ PARTICLE was discovered in 1974 as a narrow resonance in the masses of virtual photons that decayed into electron-positron pairs. The colored distribution represents the yield of masses obtained when the detection spectrometer was run with the bombarding particles at a normal intensity; the white distribution, the yield when the intensity was cut by 10 percent. The resonance at 3.1 GeV, which showed up clearly in both runs, was interpreted as a highly resolved version of the shoulder found at Brookhaven in 1968. The J/ψ particle pointed to the existence of a fourth quark, labeled *c* for "charm," and a corresponding antiquark, labeled $\bar{c}$.

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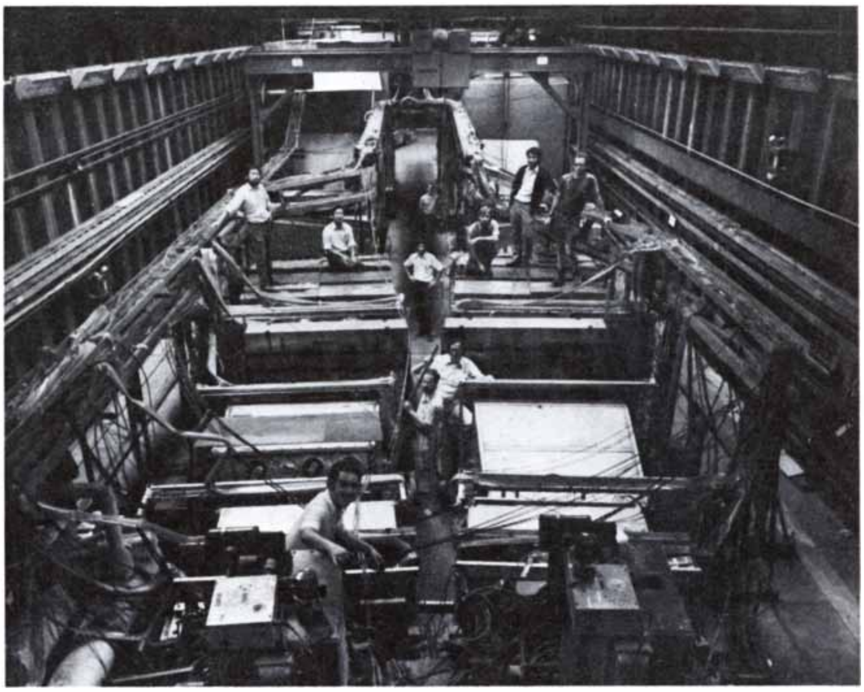
of only the other four quarks. Such compelling considerations convinced most particle physicists that the upsilon is indeed an atomlike composite of a fifth kind of quark bound to its antiquark.

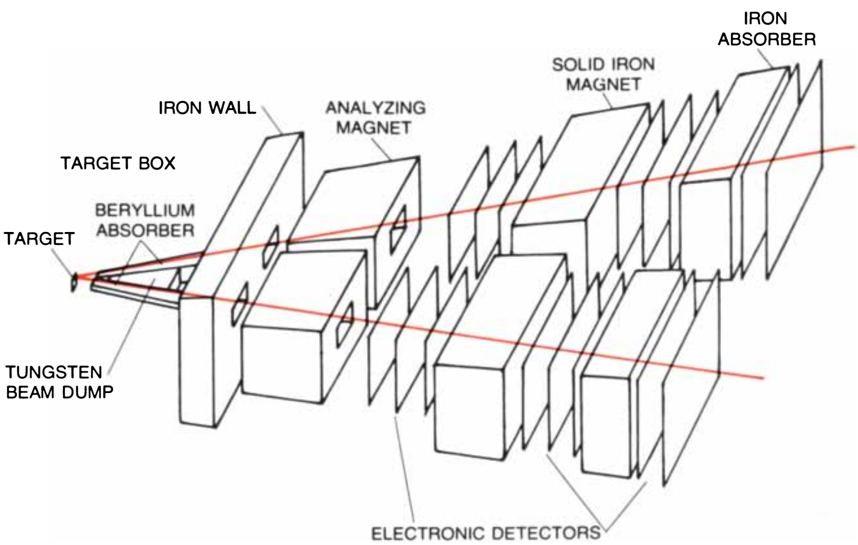
An amusing thing about the hypothesis of a fifth quark is that the reasons for which some theoretical papers introduced it turned out later to be specious. The new subparticle was supposed to explain puzzling data from scattering experiments, which on closer examination proved not to be puzzling at all. Where the fourth quark had accounted for all kinds of enigmatic phenomena, the fifth quark explained only the results of our experiment. The misinterpreted scattering data had nonetheless served a valuable heuristic purpose in stimulating speculation about the properties of particles composed of heavier quarks, properties the upsilon turned out to have. The fact that the four identified quarks were paired off as "up" and "down" and as "strange" and "charm" had led theorists to predict that if there were a fifth quark, there would also be a sixth. The eccentric names "top" and "bottom" or "truth" and "beauty" had been reserved for the two new quarks in the event they were discovered.

The upsilon resonances present physics with an embarrassment of riches: an unexpected family of new particles composed of an unexpected fifth quark. The impact of the upsilon has already been far-reaching. It has prompted searches for other heavy particles in hitherto unexplored ranges of mass, and it has shed light on the inscrutable strong force. This force, which binds quarks together into hadrons and hadrons together into atomic nuclei, is too powerful to investigate by conventional scattering and collision techniques. Yet any proposed model of the strong force, being a description of the force between a quark and an antiquark, should correctly predict the energy (or mass) levels of the upsilon family. With the upsilon, as opposed to the hadrons of lower mass, it is easier to evaluate these predictions because the velocities of massive quarks are comparatively low. This means that complicated relativistic considerations never enter the calculations. The predictions of several such theoretical models have failed, which removes them from consideration. The successful models all suggest that the new fifth quark has a charge of $-1/3$ (the charge of the electron being -1) and that the force between quarks increases with the distance between them. Such a force had been proposed to account for the failure of particle physicists to observe quarks in the free state: so much energy is needed to increase their separation that when energy is supplied, it goes into creating new quark pairs rather than into splitting old ones. The current thinking is that quarks may be permanently confined to composite structures.



FERMILAB APPARATUS detected the upsilon. The bombarding protons and the target nucleons collided at a point just out of sight in the foreground. The electromagnets, located at the left and the right in front of the man in the foreground, deflected the muon pairs so that their energies and separation angles could be measured. The two components of each muon pair traveled through different arms of the detectors. Six feet wide, six feet high and 100 feet long, the two arms extend from the electromagnets to where the man in the rear is standing.

The confirmation of this suggestion and a better understanding of the strong force may not come, however, from the study of upsilons created in proton accelerators, such as the ones with which we worked at Brookhaven and Fermilab. The production process is too complex. For example, the initial collision at Fermilab involves three quarks in the proton projectile smashing into three quarks in the target nucleon. The next step in the demystification of quark forces will come when physicists are able to intensively study upsilons that have been produced in storage-ring machines in which electrons and positrons circulate in opposite directions and collide with one another. These machines will provide cleaner and more highly resolved data. Indeed, they already have.



BERYLLIUM ABSORBER was used to screen out nuclear debris in the Fermilab experiment because beryllium affects the trajectories of muons much less than iron does. The tungsten beam dump collected bombarding protons that missed the target nucleons. This schematic diagram is a side view of the apparatus seen head on in the photograph at the top of the page.

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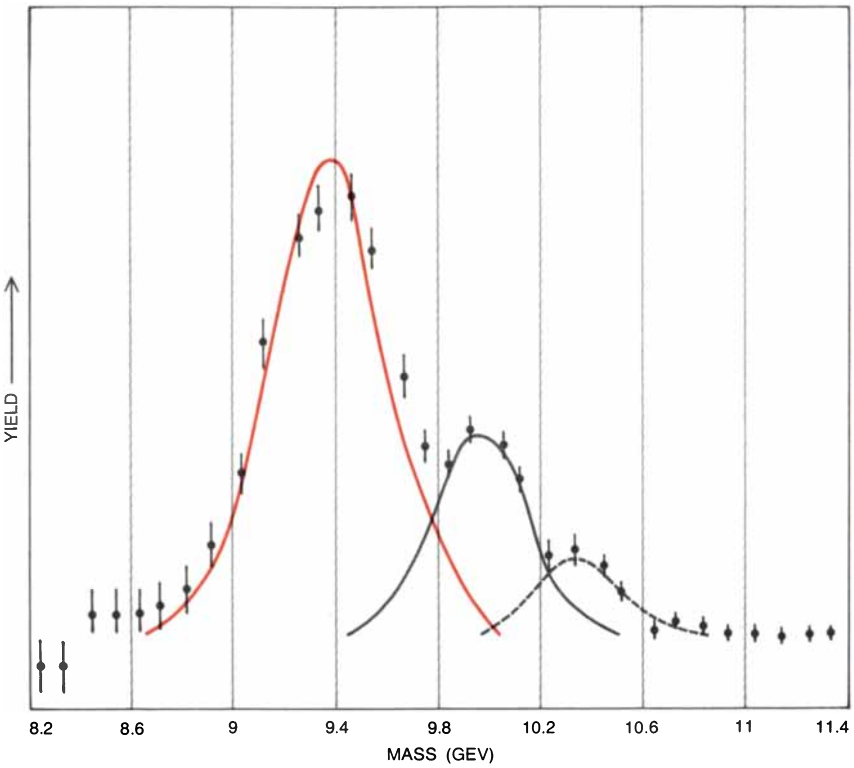

THREE CLOSELY SPACED RESONANCES characterize the upsilon. With a lowest state at 9.4 GeV and excited states at 10.0 and 10.4 GeV, the particle was interpreted as consisting of a massive fifth quark bound to its antiquark. The upsilon's spectroscopy will be clarified by experiments with storage-ring accelerators, and the search for a sixth quark has already begun.

In April a group of workers at the DESY (for Deutsches Elektronen Synchrotron) laboratory in Hamburg modified their electron-positron storage ring to look for the upsilon. They found it at 9.46 GeV and were able to place an upper bound of 7 MeV on the width of its resonance. (This is a substantial improvement on our value of 100 MeV.) Their data also suggest a −1/3 charge. The spectroscopy of the upsilon system will surely be worked out in detail over the next few years when powerful new storage rings are completed at Hamburg,

PARTICLE	SYMBOL	MASS (GEV)
PHOTON	γ	0
NEUTRINO	ν	0
ELECTRON	e	.0005
MUON	μ	.105
PI MESONS	π^0 $\pi^\pm$	.135 .140
K MESONS	$K^\pm$	.494
PROTON	p	.938
NEUTRON	n	.940
PHI	ϕ	1.020
LAMBDA	Λ	1.116
CHARMED MESONS	D^0 D^+	1.863 1.868
CHARMED LAMBDA	Λ_c	2.260
J OR PSI FAMILY	J/ψ ψ'	3.098 3.684
UPSILON FAMILY	Υ Υ' Υ''	9.4 10.0 10.4

PARTICLE MASSES are listed in ascending order. The upsilon, with a ground-state mass equivalent to an energy of 9.4 GeV, is the heaviest particle yet discovered. It is three times heavier than the J/ψ, which is the second most massive particle, and 19,000 times heavier than the electron. Particles incorporating quarks of a sixth kind would weigh more than the upsilon.

Stanford and Cornell University. Physicists will be looking for the sixth quark, the expected mate of the fifth, and they will be searching for particles made up of combinations of the six quarks.

As accelerator techniques advance, physicists will undoubtedly continue to discover new subatomic entities. The proliferation will raise deep, unsettling questions. Are the kinds of quark limited in number? If there are six, why not 12? If there are 12, why not 24? And if the number of kinds of quark is large, does it make sense to call the quarks elementary? The history of science suggests that the proliferation of physical entities is a sign the entities are not elementary. The chemists of the 19th century reduced the apparently infinite variety of chemical substances to some 36 elements, which escalated over the years to more than 100. As indivisible, ultimate constituents of matter the chemical elements simply proved to be too many. In the 1930's it was discovered that all the elements were made up of electrons, protons and neutrons. After World War II these particles were joined by dozens of others: pions, kaons, lambda particles and so on. Again there were too many. Then it seemed that all of these could be reduced to three quarks. Now experiments indicate that a fourth and a fifth quark exist. Are they also too many? Will simpler structures from which quarks are made soon be proposed? Is it possible that there are no elementary particles at all, that every entity in nature has constituent parts? Or will the ultimate simplicity that most physicists believe in be lodged in the mathematical groups that order the particles rather than in truly elementary objects?

Putting aside these last highly speculative ideas, most physicists despair of addressing such questions because of the difficulty, if not impossibility, of examining a quark in isolation. Yet the experience with the upsilon particle indicates that in spite of this difficulty detailed knowledge of the motions and forces of quarks can be acquired. The apparent inseparability of these entities should not in itself block the path of inquiry. Consider the lesson physicists should have learned from the electron. The development of the theory of the electron would probably have been slowed but not otherwise hampered if electrons had only been observed bound in atoms and never in the free state. This is an experimentalist's response to the prophets of gloom who view the confinement of quarks as an ultimate limitation on knowledge: a wall erected by nature to hide its last secrets forever. And who is to say that physicists will never build an ultrapowerful accelerator that could overcome the confining force and liberate the quark?

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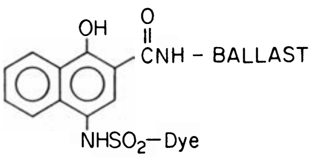
Hammett's sigma values helped

Now that well over a million Kodak instant cameras are out working, word of the color performance of Kodak instant print film PR-10 is getting around. Organic chemistry students doing academic exercises based on the Hammett equation and wondering where it all leads may be heartened by the kind of talk that went on in the Kodak Research Laboratories when the three image dyes for this film were being designed.

Just like the teams who worked on each of the many other segments of the project, the folks who had to come up with the image dyes considered *theirs* the most crucial and toughest.

The concept called for a set of dye releasers—compounds to be oxidized by an electron transfer agent—no longer called a developer because it recycles—donating electrons to neutralize Ag^+ and regenerating itself by taking electrons from the dye releaser,



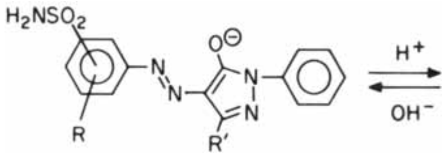
The oxidation in a highly alkaline environment releases the ionic entity $\bar{N}HSO_2$-Dye. This entity must survive unchanged through a pH range of 14 to 4, diffuse quickly through several gelatin-based layers, make its way past a gaggle of other chemical species that are there for various jobs, and attach itself firmly by ionic bonds and van der Waal's forces to a polymeric cationic mordant in the receiving layer. The negative charge that spreads over the combination as a whole of the sulfamoyl group and the π-electron cloud of the chromophore it has in tow is the key both to the mobility and to the final immobility.

A seminal paper by L. P. Hammett appeared in 1935 in *Chemical Reviews* 17:125. It did much to make the phenomena of organic chemistry quantitatively predictable, bringing order to masses of empirical data about the effect on reaction rates and equilibria of a given substituent in the meta- and para-positions on an aromatic nucleus. The relationship that pulls things together rather well is

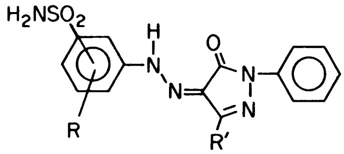
$$\log \frac{K}{K_0} = \rho\sigma$$

where, for specified reaction conditions, K is the equilibrium constant for an aromatic reactant, K_0 the constant for benzoic acid so substituted, ρ a constant that characterizes the reaction, and σ one that characterizes the behavior of that substituent in the meta- or para-position as the case may be. The σ-value then turns out to be interpretable as the tendency of the substituent to push electrons toward the reaction site or draw them away, according to whether σ is negative or positive respectively. That being the case, one might expect σ-values to help predict not only ease of ionization but also shifts in absorption maxima. Both, of course, were vital to our endeavor.

Cross-purposes between hue considerations and ionization ease came to a head in selecting R and R′ for our yellow dye:

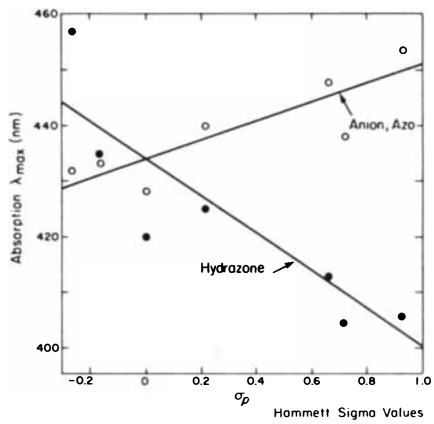


azo anion



hydrazone

Plots like the following showed us that loss of the ionic state could shift hue badly:



As any organic major struggling with a Hammett question on an exam can plainly see, such plots also show that choosing the substituents for σ-values near the intersection of the two lines would avoid such troubles.

Kodak

Nice, but to show the colors we have to know where the electrons are.

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The man who simplified housing bought a Honda Civic.

You can imagine our feeling of satisfaction when we discovered that R. Buckminster Fuller had walked into Darling's Honda in Bangor, Maine, and bought a Honda Civic® CVCC® Hatchback.

Buckminster Fuller is, after all, one of history's most original and prolific thinkers. As an architectural engineer, philosopher, mathematician, and educator, he has spent over half a century finding simple, economical ways to improve our lives.

What's more, he knows a good deal about automobiles, having owned 43 different cars over the years.

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Of course, you may know Bucky Fuller best for his masterpiece of simplicity, the geodesic dome. This ingenious structure is one of the strongest and most efficient means of enclosing space yet devised by man. More than 150,000 geodesic domes have been built, ranging in size from small dwellings to a railroad roundhouse big enough to cover a football field.

Which brings us back to the subject of automobiles. In 1933 Bucky Fuller designed and built the Dymaxion Car. It rode on three wheels and steered by a single wheel in the rear. This design made it highly maneuverable and easy to park. It even had front-wheel drive. Sound familiar?

Here's what he told us about his Honda Civic CVCC: "Its handling feels better to me than any other car I've ever owned – except my Dymaxion."

There. Isn't that nice? And isn't it wonderful when someone like Buckminster Fuller appreciates what we've done.

HONDA

We make it simple.

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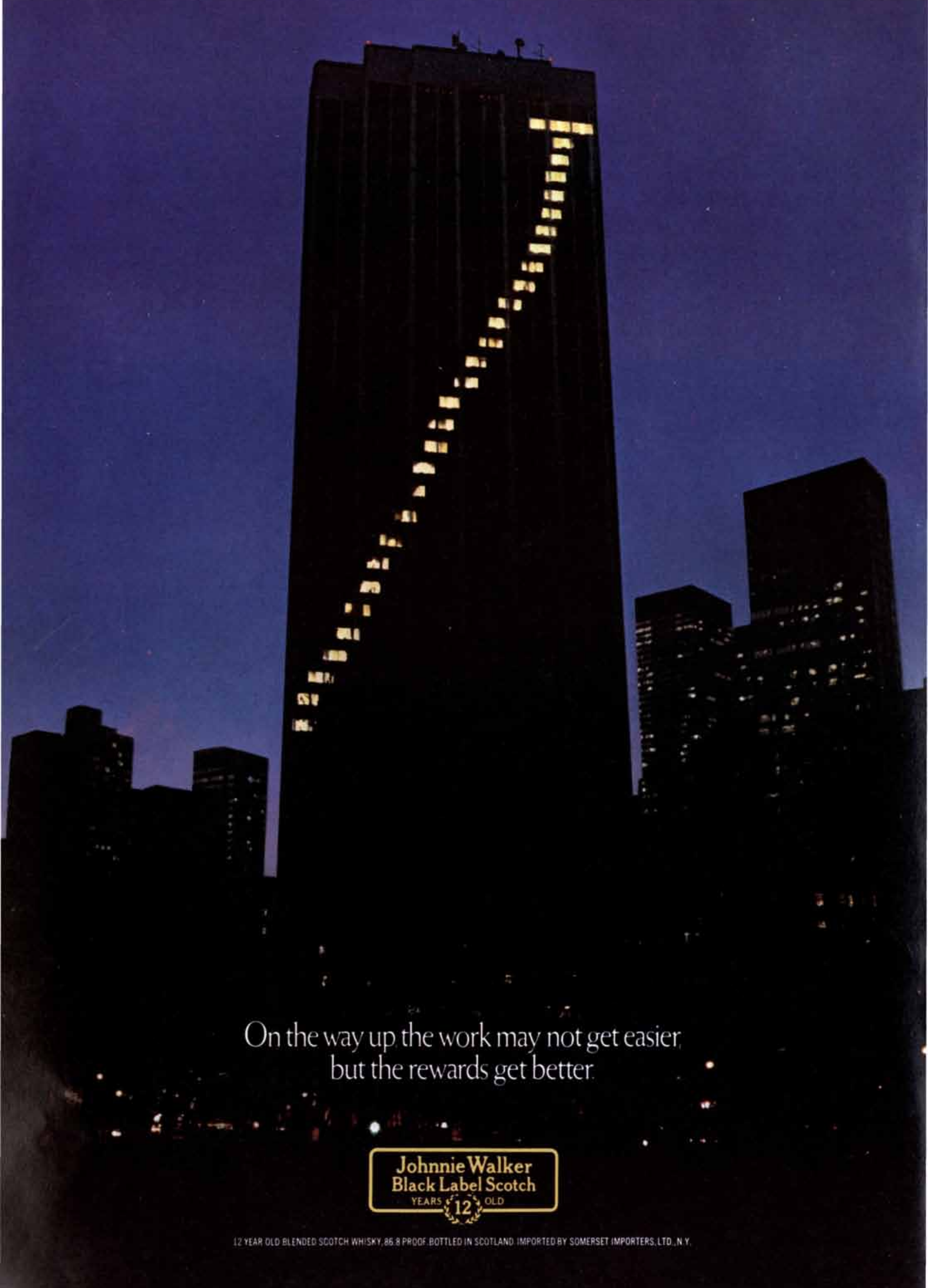

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