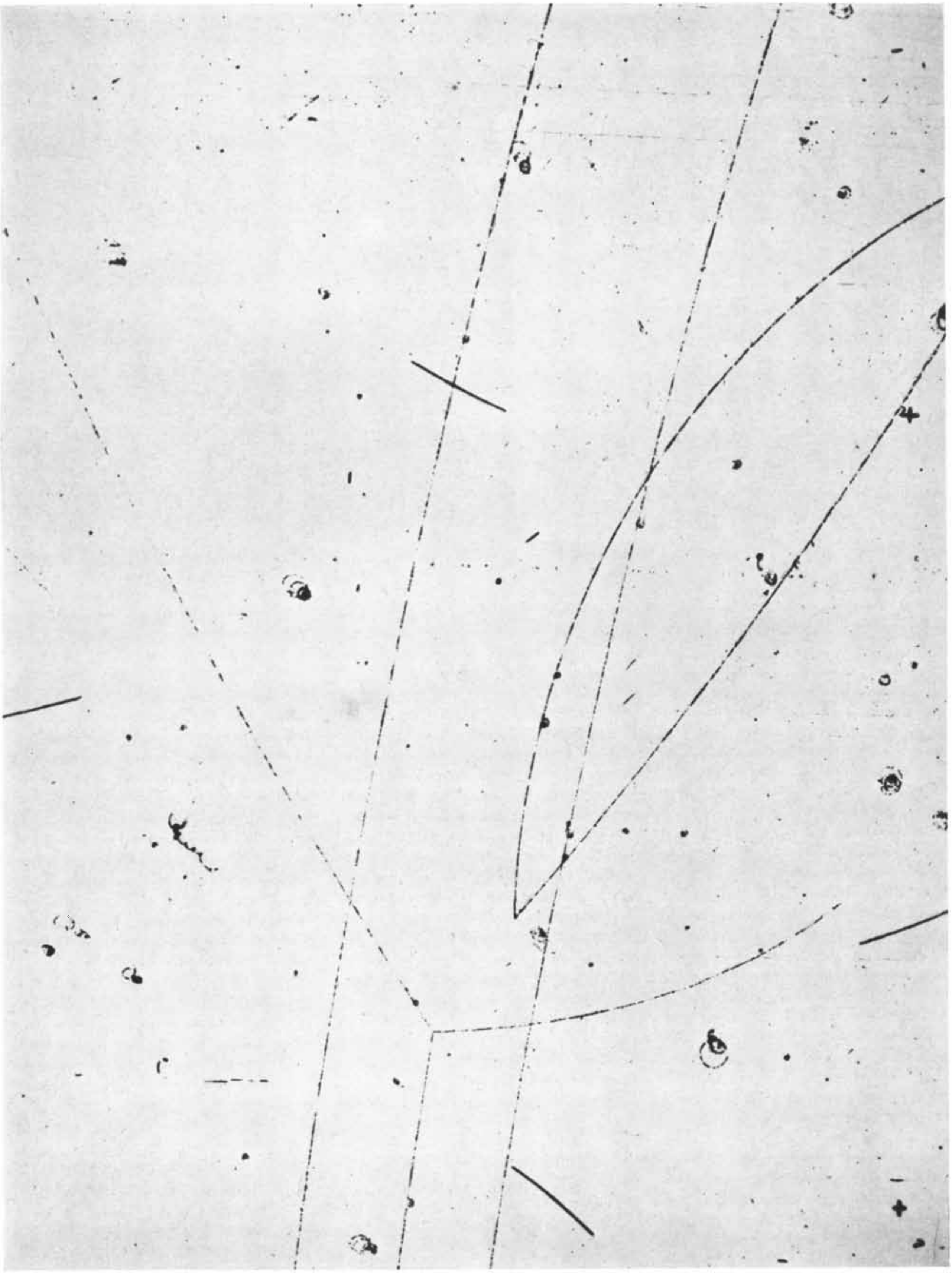


Y* RESONANCE PARTICLE and a negative pion (π^- *from O in drawing at right*) are produced in this bubble-chamber collision between a negative K meson ($\bar{K}^-$) and a proton at *O*. The resonance particle disintegrates, before it can leave a track, into a neutral lambda particle, which leaves no track (*broken line*), and a positive pion (π^+). The lambda decays into a proton (p^+) and a nega-

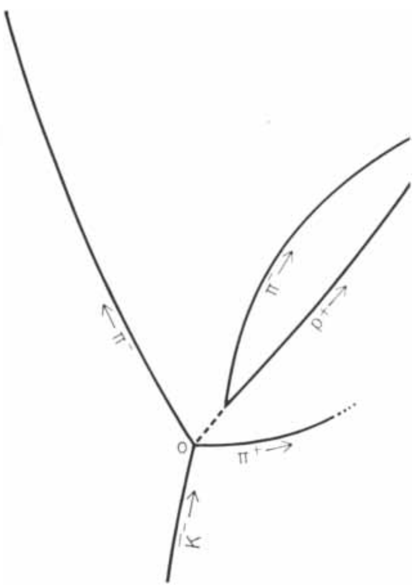
RESONANCE PARTICLES

Most of the 32 fundamental particles of matter decay rather quickly. There are still other particles that decay even more quickly. It now seems that the latter are "resonant" associations of other particles

by R. D. Hill

When is a particle "fundamental"? The fact that most subatomic particles decay quite quickly into other particles has made this a perennial question of physics. Now the difficulty is compounded by a new group of "particles" that are even more evanescent than the particles known earlier.

The list of "old" particles, which are generally considered fundamental and which I shall call Type I, has been static for some time [*see illustration on page 41*]. It still consists only of those particles mentioned as discovered or predicted in an article that appeared in SCIENTIFIC AMERICAN more than five years ago [see "Elementary Particles," by Murray Gell-Mann and E. P. Rosenbaum; SCIENTIFIC AMERICAN, July, 1957].



tive pion (π^-). The photograph was made by the experimental team under Luis W. Alvarez at the Lawrence Radiation Laboratory.

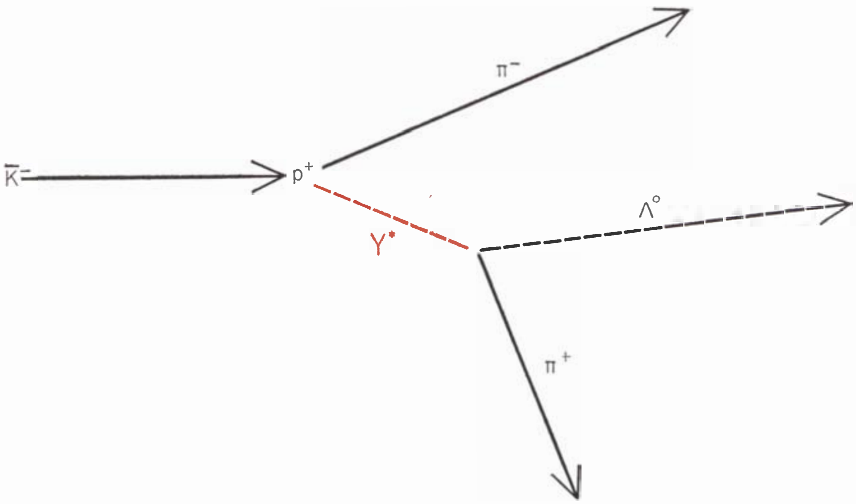
Apart from the inherently stable particles, most of the Type I particles decay in about a ten-billionth of a second. This lifetime gives them a chance to move measurable distances in a detector such as a bubble chamber. The new particles, which I call Type II, decay in about the time it takes for light to move a distance equal to a few diameters of an atomic nucleus. Their lifetimes are measured in hundred-thousandths of a billion-billionth of a second (10^{-23} second)—far too short a time to leave visible tracks or to be observed directly in any way. Their existence can only be inferred by studying the Type I particle products of their disintegrations. The question is: Were they ever autonomous particles or were they merely a group of separate pieces that moved together for a short time before flying apart? Physicists have avoided the question by calling the particles "resonances," implying that they may indeed have been temporary associations of other particles.

How is their existence detected at all? To help the reader understand the way in which they were found I shall begin by describing a fanciful experiment in classical physics, that is, the kind of physics that obtained before the introduction of quanta and relativity. Like all classical explanations of quantum and relativistic events, the analogy is far from perfect. It should nonetheless serve to provide a rough idea of what is involved.

Suppose an odd kind of artillery shell is made by gluing together three pieces of strong glass around an explosive charge. One of the pieces is red; the other two are perfectly transparent and therefore invisible. The shell is fired, moving, let us suppose, on a straight trajectory at a constant speed. As observers we move parallel to the shell in an airplane traveling at the same speed. When the shell explodes, it breaks into its three component pieces. The center of mass of these pieces continues to move in its original direction at its original speed, according to the law of the conservation of momentum. We too continue to move in this direction and at this speed. Therefore it is as if the shell and we were both stationary when the shell exploded. We are observing in the "center-of-mass system" of the exploding fragments.

Since two of the three pieces are invisible, after the explosion we can see only the red piece. We measure its speed with respect to our own position. If we perform the experiment a large number of times, we will obtain a continuous spectrum of speeds of the red fragment varying from zero up to some maximum. Zero speed corresponds to the case in which all the energy in the explosive charge is carried off by the other two pieces. This will not happen often, but it can happen. More likely is a fairly equal division of energy among the three pieces. Very unlikely is a sharing of all the energy between the red piece and the other two pieces when the latter do not separate. Thus the expected speed, or energy distribution, of the observed piece is a smooth curve [*see bottom illustration on next page*].

Suppose now that the two invisible pieces are cemented together with a glue that does not give way in the explosion. Then the shell breaks only into two pieces. When we observe the speed of the red piece, we find that it is always the same, because the energy of the explosion can be shared in only one way with the invisible piece. A plot of the energy



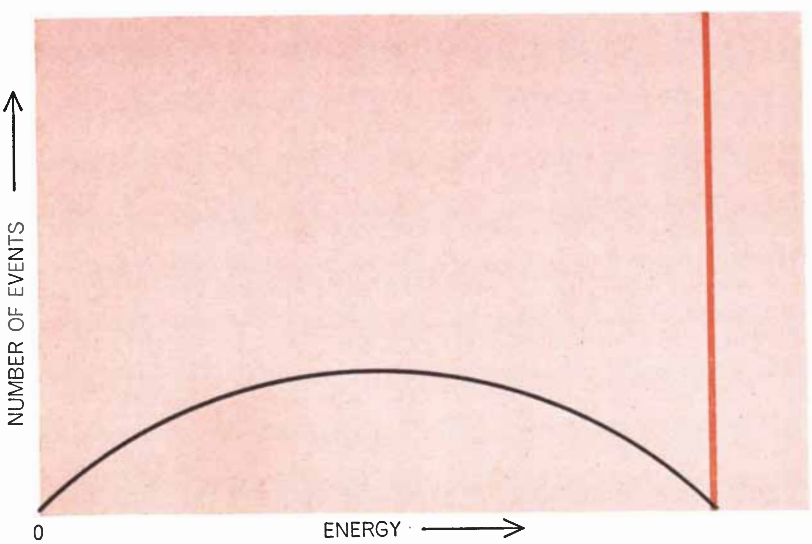
Y^* PARTICLE PRODUCTION shown in the photograph on page 38 is depicted in greater detail. The resonance particle in this instance was positive; the pion produced along with it was therefore negative. Conversely, if the particle had been negative, the accompanying pion would have been positive and the second pion (from the decay of the Y^*) would have been negative. The distance traveled by the Y^* (*broken colored line*) is of the order of 10^{-13} centimeter; thus in a bubble chamber the π^+ appears to come from the point of collision.

is a sharp line. In this way the energy distribution of the visible piece enables us to tell whether or not the invisible section broke apart in the explosion.

The first particle experiment comparable to the one I have described was performed by the bubble-chamber group at the Lawrence Radiation Laboratory of the University of California in the summer of 1960. The Lawrence Laboratory workers were shooting a beam of high-energy negative K mesons at the liquid hydrogen in the bubble chamber. They observed that when a $\overline{K}^-$ meson struck a proton (p), a small fraction of the collisions produced a neutral lambda particle (Λ°) and a negative and a positive pi meson, or pion (π^- and π^+). The reaction is written: $\overline{K}^- + p^+ \rightarrow \Lambda^\circ + \pi^+ + \pi^-$.

The experimental team (Margaret Alston, Luis W. Alvarez, P. Eberhard, Myron L. Good, W. Graziano, Harold K. Ticho and Stanley G. Wojcicki) observed a few hundred of these events and with the help of a computer analyzed the energies represented by the visible pion tracks. They found a distribution with energy peaks indicating that, in a certain fraction of the selected events, one of the charged pions (plus or minus) was recoiling from one rather than two other particles [*see bottom illustration on page 43*]. The implication was that the other pion and the lambda particle did not "break apart" immediately but remained together as a single unit at least long enough for the observed pion to recoil from it. This single unit the physicists named Y^*. The reaction was envisaged as: $\overline{K}^- + p^+ \rightarrow Y^{*+-} + \pi^{-+}$. (The double plus and minus signs refer to the fact that the charge of the Y^* was either + or − and was opposite to that of the pion.) In a very short time, so short that the Y^* can leave no visible track, this reaction is followed by: $Y^{*+-} \rightarrow \Lambda^\circ + \pi^{+-}$.

Calculations of the energies and momenta involved in the processes showed that the Y^* acts like a particle with a mass of 1,384 million electron volts (Mev). This figure is made up of the rest masses of the two particles into which the Y^* decays: 140 Mev for the pion and 1,115 Mev for the lambda, plus an additional kinetic energy of 129 Mev with which the pion and lambda fly apart. (According to the celebrated relation $E = mc^2$, energy and mass are equivalent quantities. In particle physics it is now customary to measure rest mass in energy units. The mass of an electron is .51 Mev; the mass of a proton, 938.2 Mev.) The reader will notice that the energy "spikes" representing the recoil from the Y^* are not infinitely sharp like the spike in the projectile example. Instead they have a finite, measurable width of about 60 Mev. This width, which is made up of a spread in the energies of the various particles observed, constitutes an uncertainty in the mass-energy of the Y^*. According to the uncertainty principle of quantum mechanics, uncertainty in energy is inversely proportional to uncertainty in time. An infinitely sharp spike would have an energy uncertainty of zero and therefore an infinite time uncertainty. This is the same as saying that the particle or state whose energy is represented "lives" forever; that is, it is completely stable. An energy uncertainty of 60 Mev, on the other hand, corresponds to a time uncertainty of something on the order of 10^{-23} second. This is the period



DISTRIBUTION OF ENERGY to one of three pieces of an exploding shell (in the imaginary experiment described in the text) over a number of events can be represented by a smooth curve. But if two of the three pieces always stick together, the third piece will, in theory, always receive the same amount of energy; its energy curve becomes a straight line.

within which the Y^* can exist as a separate entity; in other words, it is a measure of its average lifetime.

What exactly is the Y^*? Is it a pion and a lambda particle traveling briefly together before they take separate paths? Or is it an elementary particle that turns into a pion and a lambda particle in about 10^{-23} second? No one really knows. It may even be that with such short lifetimes the distinction is not meaningful. Whatever might be the final decision on this point, the current usage is to describe the Y^* as a resonance particle. The basis of the term "resonance" is as follows.

After the Y^* had been found its discoverers at once pointed out its similarity to a previously known resonance: the resonance between the pion and the proton (or neutron). According to the present convention the resonance could be called an N^*, N representing a nucleon (proton or neutron). This had been discovered in quite a different way. In 1952 Enrico Fermi and his colleagues at the University of Chicago were carrying out experiments in which a beam of pions was scattered by protons. They, and somewhat later other workers at the Carnegie Institute of Technology, found that the cross section, which is a measure of the probability, of scattering increased sharply beginning at a beam energy of about 100 Mev and continued to increase up to nearly 200 Mev, the highest-energy pion beam available from the accelerators of the time. When the three-billion-electron-volt Cosmotron at the Brookhaven National Laboratory went into operation, Luke C. L. Yuan and Seymour J. Lindenbaum were able to show that the cross section reached a distinct peak at a pion energy of 195 Mev and then fell off quite sharply again.

Keith A. Brueckner, then at Indiana University, suggested that there was an unusually strong and characteristic interaction between a pion and a proton that caused them to have a resonance at this energy. The characteristic feature of such an N^* resonance is the phase, or relative timing, of the oscillations of the wave associated with the scattered pion. (Thinking of particles as waves is, of course, always permissible in quantum mechanics. The probabilities of pion-scattering at different energies are related to the changes of phase of the pion waves as they pass by and through the nucleon. The amounts of phase change can be inferred from scattering observations.) As in many other resonant vibrating systems that are encountered in physics, the phase of the scattered pion wave is shifted a quarter wavelength, or 90 degrees, at resonance, and the angle measuring the amount of shift increases and decreases smoothly on both sides of the resonance point [*see bottom illustration on page 45*].

Here too arises the question: What is the physical interpretation of the resonance? Do the target proton and the incident pion temporarily merge into a single fundamental particle—the N^*—when they are close together at the right energy or do they retain their individuality and merely interact (for example, whirl about each other) very strongly? Again the answer is uncertain, but again the answer may be meaningless. In any case the N^* behaves like a particle with a rest mass of 1,237 Mev and a lifetime even a little shorter than that of the Y^*.

In the years from 1952 to 1960 much effort went into analyzing the nature of the pion-nucleon resonance at 195 Mev and also into a search for additional resonances in the pion-scattering cross section at higher energies. Several more resonances have in fact been found, and their characteristics are now known to be different from those of the original resonance. To understand wherein lies the difference it is necessary to become acquainted with two rather technical concepts of particle physics.

One of these is reasonably straightforward in that it has an analogy in classical physics. It is angular momentum. Many fundamental particles have an intrinsic angular momentum, or spin. (Some have no spin.) In all cases a measurement of the amount in a preferred direction is quantized: it may in a particular case be $+1/2$ or $-1/2$ unit (the plus sign refers to spin in one direction; the minus, to spin in the opposite direction), $+1$, 0 or -1, $+3/2$ or $-3/2$ units and so on, but never other than integral or half-integral values. Continuing the classical particle analogy still further, in a system of two particles that revolve around each other the orbital motion gives them additional angular momentum, which is also quantized. The total angular momentum of a system of two particles consists of the sum of the spin and the orbital angular momentum. Depending on their relative directions the two may add to or subtract from each other.

The pion has no intrinsic angular momentum, or spin; the nucleon has a spin of 1/2. Analysis of the interactions of

	PARTICLE	PARTICLE CHARGE STATES	ANTIPARTICLE CHARGE STATES	MASS (MEV)	MEAN LIFE (SECONDS)
LEPTONS	NEUTRINO	ν_e, ν_μ	$\bar{\nu}_e, \bar{\nu}_\mu$	0	STABLE
	ELECTRON	e^-	e^+	.51	STABLE
	MUON	μ^-	μ^+	105.66	2.2×10^{-6}
BOSONS	PHOTON	γ	γ	0	STABLE
	PION	π^0	π^0	135	2.3×10^{-16}
		π^-	π^-	139.6	2.6×10^{-8}
	K MESON	K^+	$\bar{K}^-$	494	1.2×10^{-8}
		K^0	$\bar{K}^0$	497.8	6×10^{-8} 1×10^{-10}
BARYONS	PROTON	p^+	$\bar{p}^-$	938.2	STABLE
	NEUTRON	n^0	$\bar{n}^0$	939.5	1×10^3
	LAMBDA	Λ^0	$\bar{\Lambda}^0$	1115.4	2.5×10^{-10}
	SIGMA	Σ^+	$\bar{\Sigma}^-$	1189.4	$.8 \times 10^{-10}$
		Σ^0	$\bar{\Sigma}^0$	1191.5	$< .1 \times 10^{-10}$
		Σ^-	$\bar{\Sigma}^+$	1196	1.6×10^{-10}
	XI	Ξ^0	$\bar{\Xi}^0$	1311	1.5×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	1318.4	1.3×10^{-10}

TYPE I PARTICLES are considered fundamental particles by virtue of their relatively long lifetimes, which average a ten-billionth of a second (10^{-10} second). On the basis of their masses the particles on this list have been classified as leptons, bosons or baryons.

pions and nucleons shows that their orbital angular momentum in the N* state is 1. Depending on the relative directions, the spin of the nucleon could combine with the orbital angular momentum so as to add or subtract from it and give a total spin of 1/2 or 3/2. In the case of the pion-nucleon resonance at 195 Mev the two apparently add to give an angular momentum of 3/2. If the resonance is thought of as a single particle, the two components can be considered to have merged into the spin of this particle. If the resonance is thought of as composite, there is a mixture of spin and orbital momentum.

The second concept used to classify the resonances bears the rather deceptive name of isotopic spin. The name is misleading because the word "spin" is used largely in a figurative sense. Isotopic spin is actually a series of quantum numbers, like those describing real spin, which describe the possible charge states of a particle. For example, a particle such as the lambda, which is always neutral, is said to have an isotopic spin of zero. The nucleon, which is either the positive proton or the neutral neutron, is assigned isotopic spin of 1/2. A spin of +1/2 corresponds to positive charge; a spin of −1/2, to neutral charge. Some particles, including the pion, have three possible charge states: positive, negative and neutral. The isotopic spins corresponding to these are +1, −1 and 0. When two particles form a resonant system, their isotopic spins are "aligned" in such a way as to add or subtract. In the case of the pion-nucleon resonance at 195 Mev the pion isotopic spin of 1 is added to the nucleon isotopic spin of 1/2 to give a total of 3/2. Therefore the resonance is called a 3/2, 3/2 state; that is, the isotopic spin is 3/2 and the angular momentum is 3/2.

As described above isotopic spin might seem to be an arithmetical label for charge. Actually it is more than that. The quantum numbers have a deeper physical significance that can only be hinted at here. It turns out that the probabilities of various reactions that are otherwise equivalent depend sensitively on isotopic spin. Specifically the theory predicts that the proton-scattering cross section at the N* resonance for positive pions and protons should be three times the cross section for negative pions and protons. As can be seen in the illustration on page 44, this ratio is found almost exactly in the experiments.

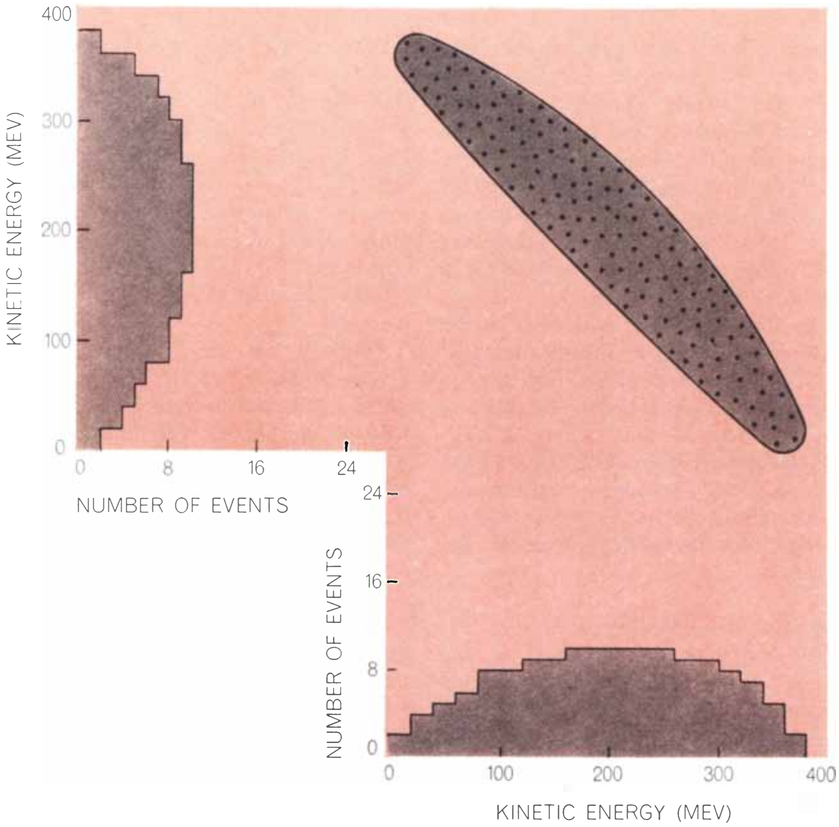
Ordinary spin and isotopic spin, then, are two of the most important properties of any particle or resonance particle. A knowledge of these quantities makes it possible to predict many of the reactions in which the particle may participate. As the illustration at the left shows, a large number of resonances have now been found. For some the ordinary spin and isotopic spin have been definitely determined. For others the values are still doubtful or, in a few cases, unknown.

The present article aims at no more than a "phenomenological" description of the resonance particles and not at a theoretical interpretation. Many theorists are busy trying to find schemes to account for them, but I shall mention these attempts only briefly.

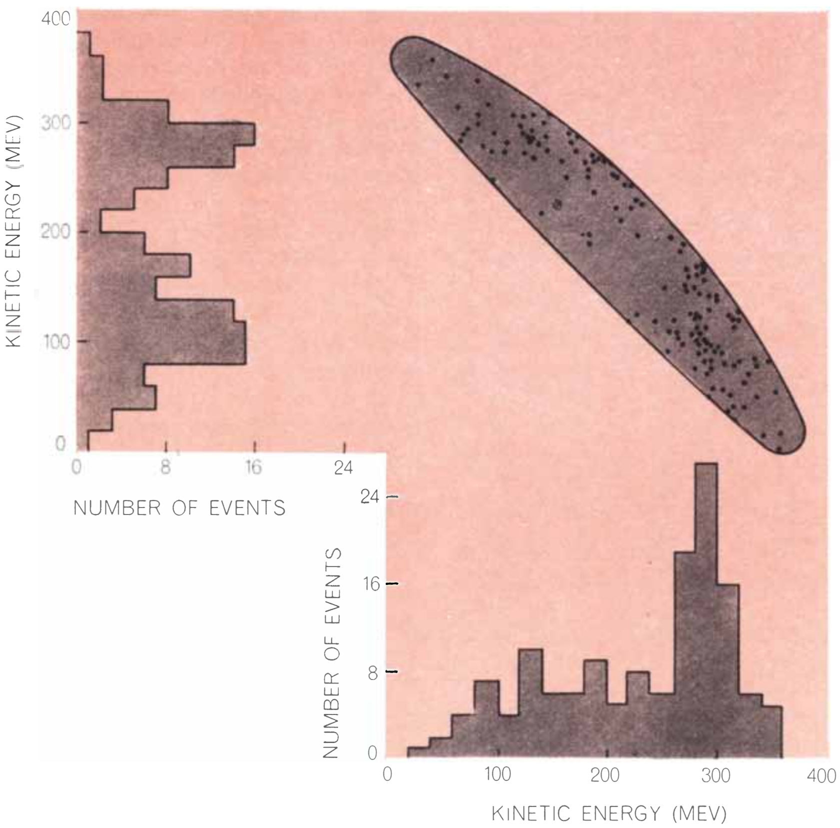
Some of the resonances were in fact predicted before they were found. In the case of the original Y* the experimenters were led to analyze their data in the way they did by an idea put forward by Murray Gell-Mann of the California Institute of Technology. He suggested that there should be a general symmetry among the interactions of pions with all the various "baryons"—

RESONANCE PARTICLE	ISOTOPIC SPIN	TOTAL ANGULAR MOMENTUM	MASS (MEV)	PARTICLE PRODUCTION
$\eta(\pi^+\pi^-\pi^\circ)$	0	0	550	$\pi^+ + d^+ \rightarrow \eta^\circ + p^+ + p^+$
$\rho(\pi\pi)$	1	1	760	$p^+ + \overline{p}^- \rightarrow \rho^\circ + \pi^+ + \pi^-$ $\pi^\pm + p^+ \rightarrow \rho^\pm + p^+$
$\omega(\pi^+\pi^-\pi^\circ, \pi^\circ\gamma)$	0	1	790	$p^+ + \overline{p}^- \rightarrow \omega^\circ + \pi^+ + \pi^-$ $\pi^+ + d^+ \rightarrow \omega^\circ + p^+ + p^+$
$K^*(K\pi)$	1/2	1	880	$\overline{K}^- + p^+ \rightarrow K^* + p^+$ $\pi^- + p^+ \rightarrow K^* + \Sigma$
$K\overline{K}$	?	?	1,020	$\pi^- + p^+ \rightarrow \overline{K}^\circ + K^\circ + n^\circ$ $\overline{K}^- + p^+ \rightarrow \overline{K}^- + K^+ + \Lambda^\circ$
$N^*(\pi N)$	3/2	3/2	1,237	$\pi^\pm + p^+ \rightarrow \pi^\pm + p^+$
$Y^*(\pi\Lambda, \pi\Sigma)$	1	3/2	1,384	$\overline{K}^- + p^+ \rightarrow Y^* + \pi$ $\pi^- + p^+ \rightarrow Y^* + \overline{K}$
$Y^{**}(2\pi\Lambda, \pi\Sigma)$	0	1/2	1,405	$\overline{K}^- + p^+ \rightarrow Y^{**} + \pi$
$N^{**}(\pi N)$	1/2	3/2	1,516	$\pi^- + p^+ \rightarrow N^{**} + \pi$
$Y^{***}(\pi\Lambda, \pi\Sigma, KN)$	0	3/2	1,520	$\overline{K}^- + p^+ \rightarrow Y^{***} + \pi$
$\Xi^*(\pi\Xi)$	1/2	> 1/2	1,535	$\overline{K}^- + p^+ \rightarrow \Xi^* + K$
$N^{***}(\pi N)$	1/2	5/2	1,683	$\pi^- + p^+ \rightarrow N^{***} + \pi$

TYPE II PARTICLES are the resonance particles. Those listed here are considered to be reasonably well established, but many of the values given are still tentative. No generally accepted nomenclature yet exists. Four are identified by Greek letters: eta (η), rho (ρ), omega (ω) and xi* (Ξ^*). The decay particles are shown in parentheses. For example, an omega particle decays into either three pions or a pion and a photon, the K* decays into a K meson and a pion, the N* into a pion and a nucleon (i.e., proton or neutron), and so on. The column at far right represents the reactions that produce the various particles; *d* represents a deuteron, or the nucleus of a heavy-hydrogen atom, consisting of one proton and one neutron. In contrast to Type I particles, the resonance particles have much shorter lifetimes, of the order of a hundred-thousandth of a billion-billionth of a second (10^{-23} second).



EXPECTED DALITZ PLOT shows the theoretical distribution of energy between the two pion products of the reaction: $K^- + p^+ \rightarrow \Lambda^\circ + \pi^+ + \pi^-$. The energy of the positive pion produced in 141 instances of this reaction can be read on the horizontal scale at bottom; the energy of the negative pion produced in the same events, on the vertical scale at upper left. The distribution of energy between the two pions in a large number of events should be more or less equal, and the energy plot for any one product should result in the type of histogram shown, which is the equivalent of a smooth curve (*see bottom illustration on page 40*). The lenticular area at upper right defines the range of values within which the energies from a single event must fall. The distribution of energies (*dots*) is uniform.



OBSERVED DALITZ PLOT of the interaction of a negative K meson and a proton is based on the studies of the bubble-chamber group under Alvarez. The energy distribution in the lenticular area is not uniform, and the plots show that the distribution of energy occurs mainly in peaks: two relatively strong peaks in the plot of the negative pion and a single stronger peak in that of the positive pion. The distribution is consistent with a reaction that produces two particles rather than three: $\bar{K}^- + p^+ \rightarrow Y^* + \pi$. The width of the strongest resonance peak is 60 Mev, which corresponds to an average lifetime for the Y^* of 10^{-23} second. This type of graphic analysis received its name from Richard H. Dalitz of the University of Chicago, who developed it to study tau-meson decay.

particles as heavy as nucleons or heavier. Since a resonance between pion and nucleon was already known, this suggested that there should also be a resonance between the pion and the lambda particle, which is one of the baryons.

Another line of theoretical work has led to the discovery of several resonances among pions. This work got its impulse from recent studies of the scattering of electrons by nucleons. Robert Hofstadter and his colleagues at Stanford University were the pioneers in this field [see "The Atomic Nucleus," by Robert Hofstadter; SCIENTIFIC AMERICAN, July, 1956], and they were later joined by Robert R. Wilson's group at Cornell University and G. R. Bishop's group at the Orsay laboratory of the French National Center for Scientific Research. Their experiments have shown that both the electric and the magnetic properties of protons and neutrons are not concentrated at a point but are distributed over a space of finite size. In other words, the experiments are depicting the electromagnetic structure of the nucleon.

That structure turns out to be analyzable into three separate parts. First, there is a core: a small, central region of positive charge that accounts for about a fourth of the total charge. Second, there is a "vector" portion that is positive in the proton and negative in the neutron and that extends over the whole nucleon; it accounts for about half of the total charge. Third, there is a positive "scalar" portion, also extending over the whole particle and contributing a fourth of the total charge.

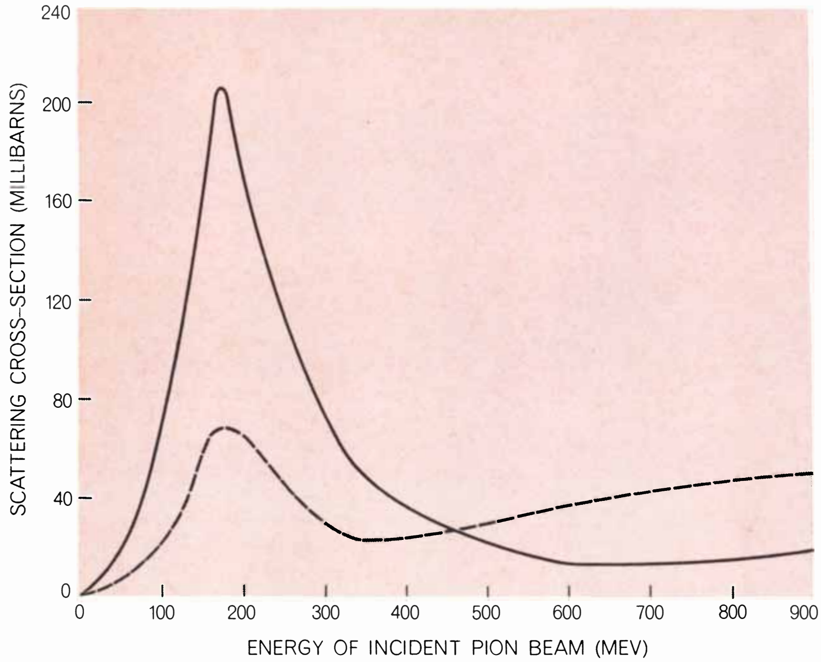
As for magnetism, part of it in the case of the proton is directly identified with the spinning charge. But there is another part, which occurs in both proton and neutron, that cannot be identified with the net over-all charge. This is known as the anomalous magnetic moment. It too turns out to consist of three components resembling those of the charge.

When the detailed pictures of the electromagnetic structure of the nucleon began to emerge, it was at once apparent that they would not fit satisfactorily into the then prevailing theory of the nucleon. All such theories are based on still another concept peculiar to quantum theory: the idea of virtual "field particle" emission. Briefly, it is believed that a proton or neutron continually emits and reabsorbs virtual pions. The time that the nucleon spends in this virtual state and the distance that the pion separates from the nucleon are consistent with the uncertainty principle. Thus for a certain fraction of the time the core of the nucleon is surrounded by a meson cloud, and it is this cloud that accounts for the extended charge and magnetic moment.

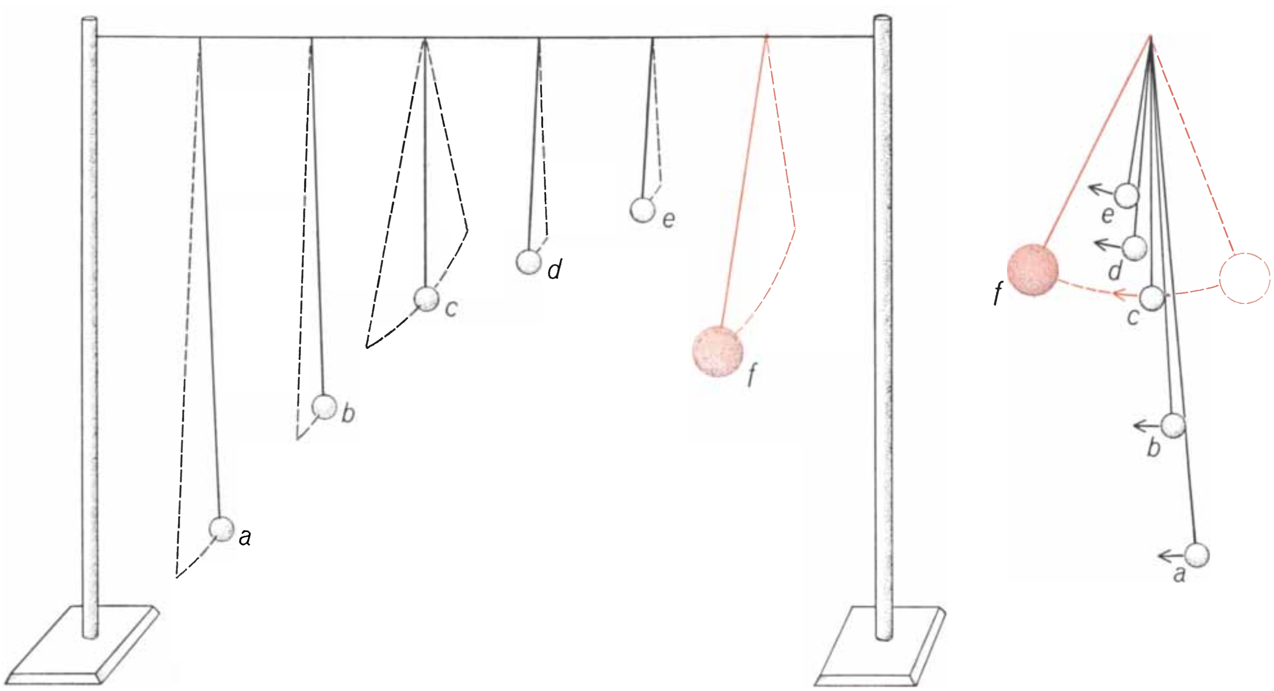
Originally the virtual-emission process was envisaged in terms of noninteracting pions. But Hofstadter's results could not be explained in this way. In 1959 William R. Frazer and Jose R. Fulco of the Lawrence Radiation Laboratory showed that the vector part of the charge and the magnetic properties would be accounted for if the nucleon emitted two pions and these entered into a strong, or resonant, interaction while they were out in the cloud. To put it another way, the calculations predicted a two-pion resonance particle, and they showed that it should have an isotopic spin of 1, an angular momentum of 1 and a mass of approximately 600 Mev.

These calculations prompted experimenters to look for a 600-Mev resonance particle in various pion-pion interactions. Evidence for it was soon found independently by a number of groups. One result, for example, showed that when a high-energy pion produces a second pion by colliding with a proton, there is a strong attraction between the two pions. Eventually experiments analogous to those outlined for the Y^* demonstrated that the resonance known as the rho particle has a mass of approximately 760 Mev, which is in good agreement with the current theory of electromagnetic structure of the nucleon.

Also in 1959 Geoffrey F. Chew of the Lawrence Radiation Laboratory pointed out that the scalar part of the nucleon electromagnetic structure could be understood in terms of another resonant interaction, this time involving three pions. Since this part of the nucleon structure is the same for proton and neutron, the isotopic spin of a three-pion resonance interaction needed to explain this feature has to be zero; that is, it must exist in only one neutral charge form. Chew suggested that it was not unreasonable to anticipate the existence of a strong three-pion resonance particle, which should have a mass approximately the same as the two-pion resonance state. It should be mentioned that Chew's suggestion of a zero isotopic-spin particle was not the first. Two years earlier



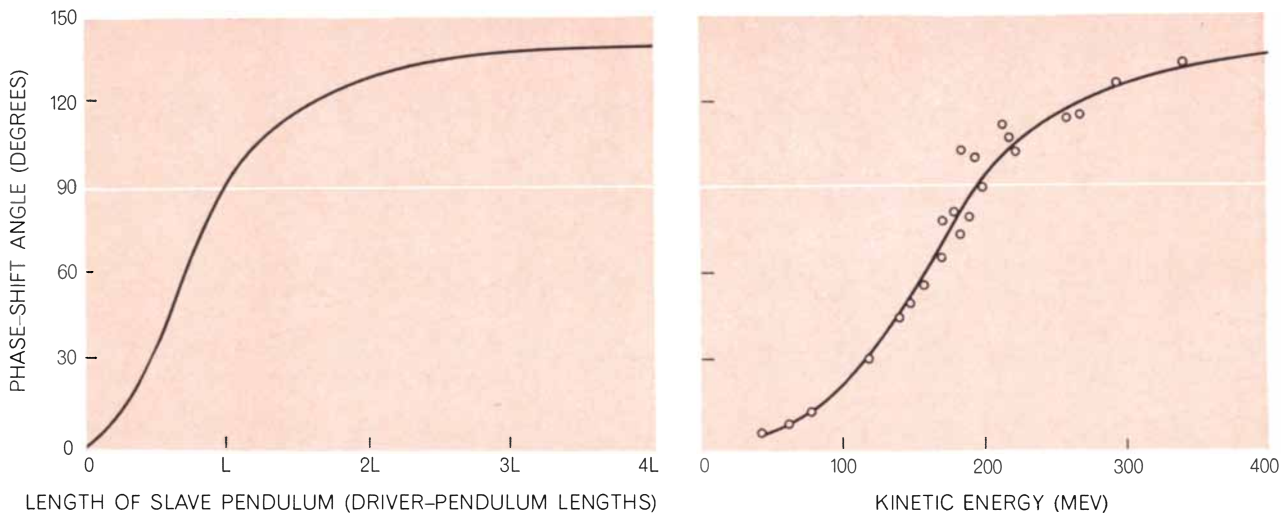
PION-PROTON RESONANCE, discovered in 1952, was the first of its kind. The two curves plot the probability that a beam of positive (*solid line*) and negative pions (*broken line*) will be scattered by protons. The scattering cross section, or probability (measured in millibarns), for positive pions begins to increase sharply at about 100 million electron volts (Mev), reaches a peak of somewhat more than 200 Mev and then falls off almost as sharply. In contrast, the resonant effect for the scattering of negative pions is only a third as strong.



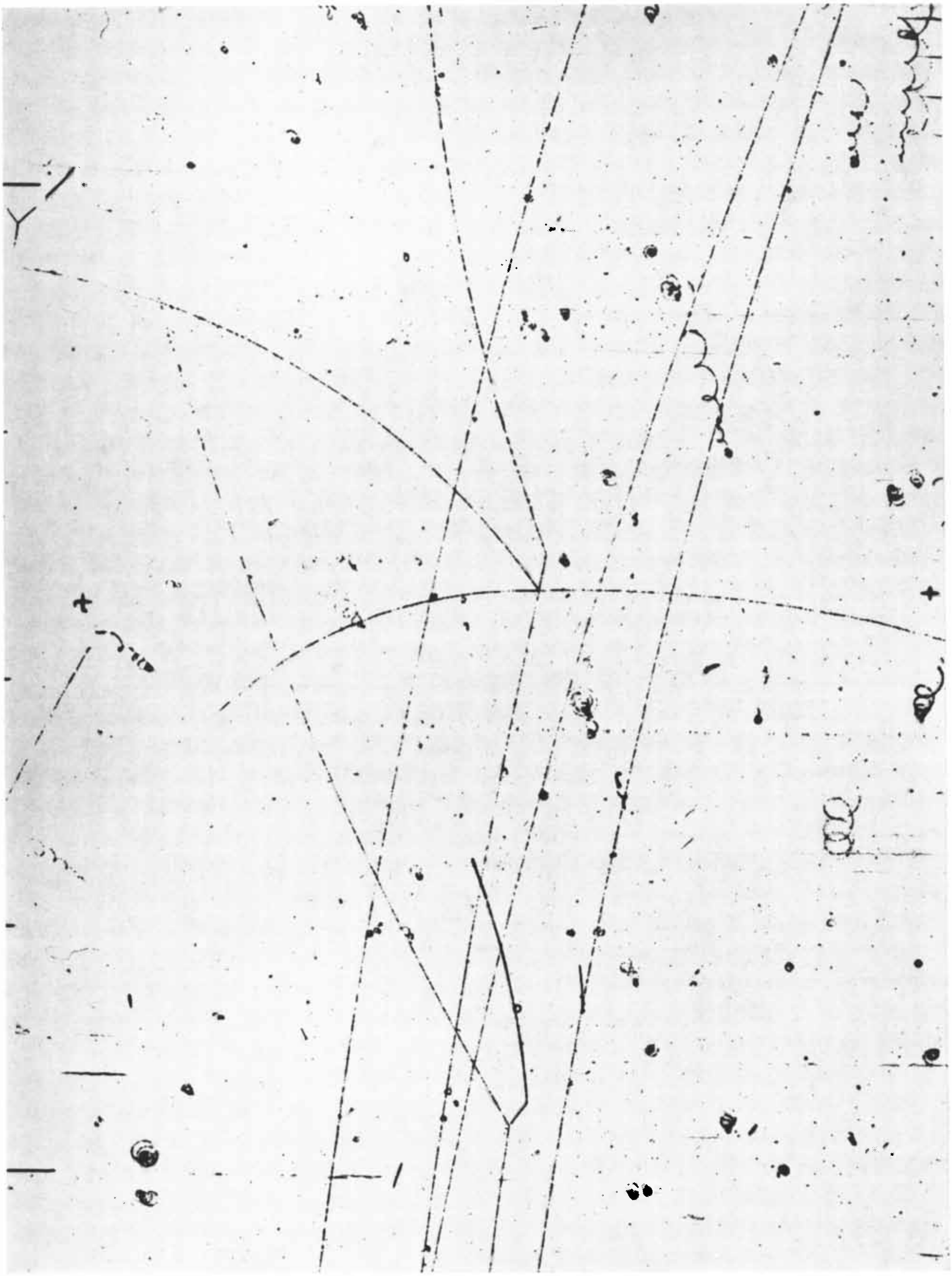
COUPLED PENDULUMS provide a mechanical illustration of a resonant system. The frequency of the driver pendulum (*f*) is greater than that of the first two "slave" pendulums (*a and b*), the same as that of the third (*c*) and smaller than that of the last two (*d and e*). The third oscillates 90 degrees out of phase with the driver (i.e., a quarter of a cycle behind it). The first two oscillate between 90 and 180 degrees behind, the last two between zero and 90 degrees behind. This lag is the phase shift (*see illustration below*).

Yoichiro Nambu of the University of Chicago had suggested the existence of a neutral heavy meson that would contribute to the electromagnetic structure of the nucleon. These ideas were clearly responsible for the research that led to the discovery of the various multiple-pion resonance states now known. Probably the most spectacular experimental discovery was that of the omega: the three-pion resonance that Chew and Nambu had predicted. The experiments were carried out by B. C. Maglic, Luis W. Alvarez, Arthur H. Rosenfeld and M. Lynn Stevenson of the Lawrence Laboratory. They studied the annihilation of antiprotons (p) encountering protons in the 72-inch liquid-hydrogen bubble chamber. Annihilations yield a wide variety of products, but the experimenters concentrated only on those that produced four outgoing pion tracks. Out of 2,500 events of this type only 800 had the following special property: in order to balance energy and momentum in the annihilation process, another neutral pion must have been present with the outgoing particles. These carefully restricted events were therefore examples of the following reaction: $p^+ + p^- \rightarrow \pi^+ + \pi^- + \pi^0 + \pi^+ + \pi^-$.

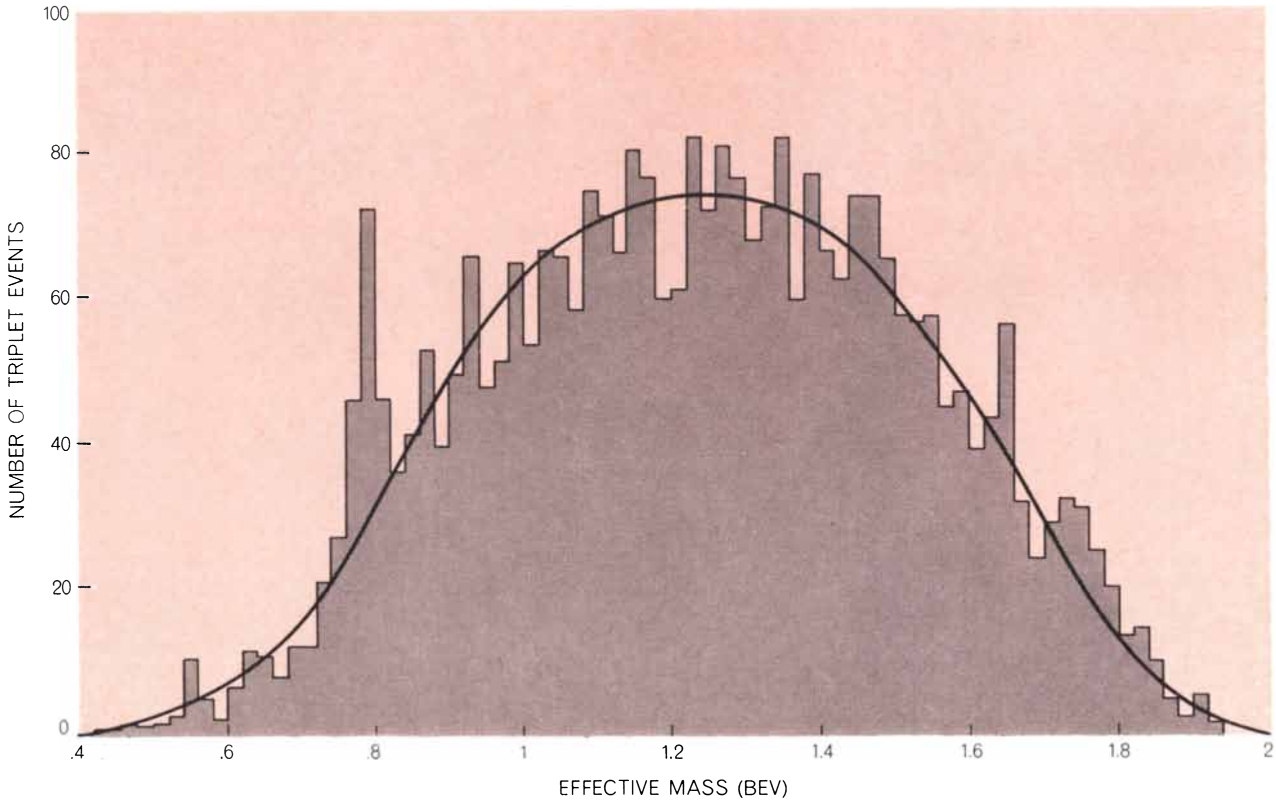
In all 800 examples of the reaction the physicists hoped to find some energy



RESONANCE EFFECT in the scattering of pions by protons becomes apparent when energy is plotted against phase shift (*graph at right*). The curve closely resembles that of the corresponding plot of phase angle against the pendulum length (*graph at left*).



PRODUCTION OF POSSIBLE Y^{**} from the collision of a negative K meson ($\bar{K}^-$ *in drawing at right*) with a proton at *O* cannot be distinguished from the direct production of a negative sigma particle (Σ^-), one negative pion and two positive pions (and possibly even a neutral pion) in this reaction, unless careful analyses are made of the energies and momenta of the particles involved.



OMEGA RESONANCE PARTICLE, a three-pion particle, was discovered in experiments carried out at the Lawrence Radiation Laboratory. Its observed mass (*peak near .8 Bev*) was 790 Mev. All the other masses tended to average out along the smooth curve.

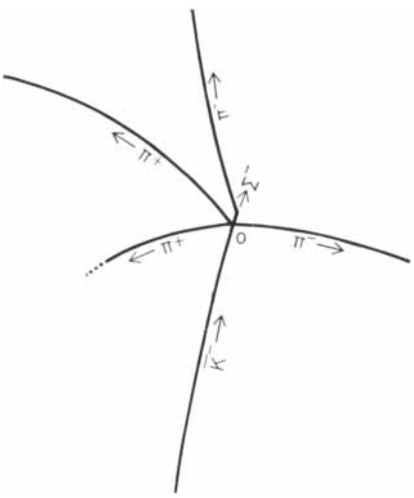
where three of the pions exhibited a resonant interaction. (Since they were looking for a neutral resonance, they knew that one of the pions would have to be neutral and the other two oppositely charged.) A further detailed analysis of the dynamics of the 800 events was then performed (using high-speed digital computers throughout) and an "effective" mass was computed for every possible combination of three of the five pions present in each event. The method was similar to that already discussed in connection with the discovery of the Y^*.

It was found that only the expected combination—namely, the π^+, π^-, π° combination—led to a group of mass values having a peak value characteristic of a single particle [*see illustration above*]. Very few of the pion triplets, in fact only 93, showed the property of being in the resonant state. Presumably almost all the other cases represented production of independent pions. Nevertheless, there were enough to point clearly at the omega particle (ω°), and to show that it is a neutral combination (π^+, π^-, π°) arising from the reaction: $p^+ + \bar{p}^- \rightarrow \omega^\circ + \pi^+ + \pi^-$. The observed mass of the omega resonance particle is 790 Mev, and its lifetime, as determined from the width of the particle resonance, is equal to or greater than 4×10^{-23} second.

At present the nature of the resonance particles is very much in question. As has been mentioned, certain theoretical ideas account fairly well for certain of the particles. But there are some particles that seem to have no such pedigree.

Of course, theoretical physicists are trying hard to find some general framework that will accommodate all the resonances. There have been several independent lines of attack, which I can do no more than to identify in a few words. One has been to regard some of the resonance particles as the quanta of certain fields, just as the photon is the quantum of the electromagnetic field and the pion the quantum of the nuclear-force field. Another approach has been to consider that all possible particles are associated with a representation of the mathematical form known as a group. A third line makes use of a new idea in the mathematics of quantum theory known as Regge poles. Here all particles are regarded as equally fundamental and equally composite, each being representable as a dynamical interaction of the others.

On this necessarily mysterious note the article closes. If the reader is mystified, so are physicists. The place of the resonance particles in the scheme of things is one of the most puzzling physical questions to which the future, one hopes, will provide the answer.



The sigma particle decays into a negative pion and a neutron, which leaves no track. Photograph was made by the Alvarez group.