3

Strangeness

The discoveries of the strange particles, 1943–1959

The elucidation of the $\pi \rightarrow \mu\nu$ decay sequence left particle physics in a relatively simple state. Yukawa's particle had been found and the only unanticipated particle was the muon, of which I. I. Rabi is said to have remarked "Who ordered that?" The question remains unanswered. The cosmic ray experiments of the next few years quickly and thoroughly destroyed the simplicity that had previously prevailed. The proliferation of new particles, many with several patterns of decay, produced great confusion. The primary source of confusion was whether each new decay mode represented a new particle or was simply an alternative decay for a previously observed particle. Continued experimentation with improved accuracy and statistics eventually resolved these ambiguities, but basic uncertainties remained. What was the nature of these particles? How were they related to the more familiar particles? The examination of these questions led to the development of the concepts of associated production, strangeness, and ultimately, parity violation and $SU(3)$.

Remarkably, another meson seems to have been discovered before the pion. Working in the French Alps in 1943, Leprince-Ringuet and L'héritier took 10,000 triggered pictures in a 75 cm x 15 cm x 10 cm cloud chamber placed inside a magnetic field of 2500 gauss **(Ref. 3.1)**. This permitted careful measurements of the momenta of the charged tracks. One of the pictures showed an incident positive particle of about 500 MeV/c momentum produce a secondary of about 1 MeV/c. By assuming the incident particle had scattered elastically on an electron and using the measured angles, Leprince-Ringuet and L'héritier determined the mass of the incident particle to be 990 $\mathrm{m_e} \pm 12\%$ ($506 \pm 61\,\mathrm{MeV}$), astonishingly close to the mass of the K^+. It was impossible that this could have been a π (whose mass was known shortly after the French result was finally published in 1946). Hans Bethe showed that the data were consistent with the incident particle being a proton only if extreme errors were assigned to the measurements.

Cosmic-ray research just after World War II centered in a few laboratories,

Old	Present	
τ	$K_{\pi 3}$:	$K^+ \rightarrow \pi^+\pi^+\pi^-$
V_1^0		$\Lambda^0 \rightarrow p\pi^-$
$V_2^0(\theta^0)$		$K_S^0 \rightarrow \pi^+\pi^-$
κ	$K_{\mu 2}$:	$K^+ \rightarrow \mu^+\nu_\mu$
	$K_{\mu 3}$:	$K^+ \rightarrow \mu^+\pi^0\nu_\mu$
$\chi(\theta^+)$	$K_{\pi 2}$:	$K^+ \rightarrow \pi^+\pi^0$
V^+, Λ^+		$\Sigma^+ \rightarrow p\pi^0, n\pi^+$

Table 3.1: Comparison of old and present nomenclature for selected decays.

including Bristol, whose group was led by Powell; Manchester, led by Blackett; Ecole Polytechnique headed by Leprince-Ringuet; Caltech, headed by Anderson; and Berkeley, led by Brode and Fretter. In 1947, the year of the $\pi \rightarrow \mu\nu$ paper of Lattes, Occhialini, and Powell, G. D. Rochester and C. C. Butler published two cloud chamber pictures showing forked tracks **(Ref. 3.2)**. One proved to be the decay of a neutral particle into two charged particles and the other, the decay of a charged particle into another charged particle and at least one neutral. Whereas the event of Leprince-Ringuet and L'héritier may have established the existence of a particle with mass between the pion and the proton, the discovery of Rochester and Butler was much more revealing. It showed there were unstable particles decaying into other particles, perhaps pions. These unstable particles could be either charged or neutral, and had lifetimes on the scale of 10^{-9} to 10^{-10} s.

Surprisingly, the discovery of Rochester and Butler was not confirmed for over two years. Before that occurred, the Bristol group, using emulsions of increased sensitivity, observed the decay of a charged particle into three charged particles (**Ref. 3.3**). This particular decay came to be known as the tau meson. A guide to some of the old notation for the unstable particle decays is given in Table 3.1.

Confirmation of the events of Rochester and Butler was produced by the group at Caltech, which included C. D. Anderson, R. B. Leighton, and E. W. Cowan. Both neutral- and charged-particle decays were observed in their cloud chamber exposures, but no accurate estimate of the masses of the decaying particles was possible. A year later, in 1951, the Manchester group published results they obtained by taking their cloud chamber to the Pic-du-Midi in the Pyrenees. Studying the neutral decays, they were able to infer the existence of two distinct neutral particles, V_1^0 and V_2^0.

The progress on the charged-particle decays was slower. There was confirmation of the tau meson decay. In addition, O'Ceallaigh, working at Bristol, produced emulsion evidence for the decay of a charged particle into a μ^+ and one or more neutrals, the κ decay (Ref. 3.4). In one exposure, the μ^+ was convincingly identified through its decay into e^+. (See Figure 3.7).

Figure 3.7: A κ (K) meson stops at P, decaying into a muon and neutrals. The muon decays at Q to an electron and neutrals. The muon track is shown in two long sections. Note the lighter ionization produced by the electron, contrasted with the heavy ionization produced by the muon near the end of its range. The mass of the κ was measured by scattering and grain density to be 562 ± 70 MeV (Ref. 3.4).

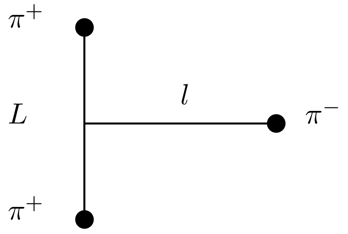

Figure 3.8: Diagram for the angular momentum in τ^+ meson decay. The $\pi^+\pi^+$ angular momentum, L, must be even. The orbital angular momentum, l, of the π^- must be added to L to obtain the total angular momentum (that is, the spin) of the tau.

While the tau meson mass had been measured quite well, the mass of the V_2^0 or θ^0 was not determined until the work of R. W. Thompson and co-workers at Indiana University (**Ref. 3.5**). They were able to establish a Q value for the decay of 214 MeV, in good agreement with the present value ($M_K - 2M_\pi = 219$ MeV). This indicated that the tau and theta mesons had just about the same mass and set the stage for the famous puzzle about the parities of these particles.

The year 1953 marked a turning point in the investigation of the new V-particles. The great achievements of cosmic-ray physics in exploring the new particles was summarized in a meeting at Bagnères-de-Bigorre in France. The V_1^0 was well established, as was the tau. There were indications of both positive and negative hyperons (particles heavier than a proton). The negative hyperon was observed in a cascade that produced a neutral hyperon that itself decayed (Refs. 3.6, 3.7) There was a κ, which decayed into a muon plus neutrals, and a χ, which decayed into a charged pion plus neutrals. The $\theta \rightarrow \pi^+\pi^-$ was established, too.

At the Bagnères Conference, Richard Dalitz presented his analysis of the tau that was designed to determine its spin and parity through its decay into three pions. Some immediate observations about the spin and parity of the tau are possible. If there is no orbital angular momentum in the decay, the spin is zero and the parity is $(-1)^3$ because the parity of each pion is -1, and thus $J^P = 0^-$. The system of $\pi^+\pi^+$ can have only even angular momentum because of Bose statistics. Dalitz indicated this angular momentum by L and the orbital angular momentum of the system consisting of the π^- and the $(\pi^+\pi^+)$ by l. See Figure 3.8. Then the total angular momentum, J, was the vector sum of L and l. If $L = 0$, then $J = l$, and $P = (-1)^{J+1}$. For $L = 2$, other combinations were possible. Dalitz noted that since the sum of the pion energies was a constant, $E_1 + E_2 + E_3 = Q$, each event could be specified by two energies and indicated on a two-dimensional plot. (Here we are using kinetic energies, that is relativistic energies less rest masses.) If E_1 corresponds to the more energetic π^+ and E_2 to the less energetic π^+, all the points fall on one half of the plot. See Figure 3.9. If the decay involves no angular momentum and there are no effects from interactions between the produced pions, the points will be evenly distributed on the plot. Deviations from such a distribution give indications of the spin and parity. For example, as $E_3 \to 0$, the π^- is at rest and thus has no angular momentum. Thus $l = 0$, $J = L$ and $P = (-1)^{J+1}$. Hence if the tau is *not* in the sequence $0^-, 2^-, 4^-, ..$ there should be a depletion of events near $E_3 = 0$. As data accumulated in 1953 and 1954, it became apparent that there was no such depletion and thus it was established that τ^+ had J^P in the series $0^-, 2^-, \ldots$

The decay distribution for a two-body decay is given by Fermi's Golden Rule (which is actually due to Dirac) in relativistic form:

$$d\Gamma = \frac{1}{32\pi^2}|\mathcal{M}|^2\frac{p_{cm}d\Omega}{M^2}$$

Here $d\Gamma$ is the decay rate, p_{cm} is the center-of-mass momentum of either final state particle, M is the mass of the decaying particle and $d\Omega$ is the solid angle element into which one final state particle passes. $\mathcal{M}$ is the Lorentz invariant amplitude for the process. The amplitude $\mathcal{M}$ will involve the momenta of the various particles and factors to represent the spins of the particles.

For three-body decays there are more final state variables. If the particles are spinless or if polarization is ignored, however, there are only two variables necessary to specify the final state. They may be chosen to be the energies of the final state particles. The Golden Rule then takes the form

$$d\Gamma = \frac{1}{64\pi^3 M}|\mathcal{M}|^2 dE_1 dE_2$$

Thus if $\mathcal{M}$ is constant, $d\Gamma \sim dE_1 dE_2$ and the events fall evenly on the Dalitz plot.

By examining the Dalitz plot, inferences can be drawn about spin and parity. Consider the $\tau \to 3\pi$. If the tau is spinless and the values of L and l are zero, $\mathcal{M}$ should be nearly constant. (Actually, it need not be absolutely constant. It may still depend on the Lorentz invariant products of the momenta in the problem.) Suppose, on the contrary, tau has spin 1. Then it will be represented by a polarization vector, $\boldsymbol{\epsilon}$. The amplitude must be linear in $\boldsymbol{\epsilon}$. If we treat the pions as nonrelativistic, it suffices to consider just three-momenta rather than four-momenta. The amplitude, in order to be rotationally invariant, must be the dot product of $\boldsymbol{\epsilon}$ with a vector made from the various pion momenta. In addition, because of Bose statistics, the amplitude must be invariant under interchange of the two π^+'s, particles 1 and 2. Two examples are

$$\boldsymbol{\epsilon} \cdot \mathbf{p}_3$$

$$\boldsymbol{\epsilon} \cdot (\mathbf{p}_1 - \mathbf{p}_2) \times \mathbf{p}_3 \; (\mathbf{p}_1 - \mathbf{p}_2) \cdot \mathbf{p}_3$$

Both represent spin-1 decays. The parity of the decaying object, assuming parity is conserved in the decay, is determined by examining the behavior of the quantity dotted into $\boldsymbol{\epsilon}$. In the first case, the single momentum contributes (-1) to the parity since the momenta are reversed by the operation. In addition, the intrinsic parities of the three pions contribute $(-1)^3$. Altogether, the parity is even, so the state is $J^P = 1^+$. In the

Figure 3.9: Dalitz plots showing worldwide compilations of tau meson decays ($\tau^+ \to \pi^+\pi^+\pi^-$) as reported by E. Amaldi at the Pisa Conference in June 1955 [*Nuovo Cimento Sup.* IV, 206 (1956)]. On the left, data taken in emulsions. On the right, data from cloud chambers. There is no noticeable depletion of events near $E_3 = 0$, *i.e.* near the bottom center of the plot. Parity conservation would thus require the tau to have $J^P = 0^-, 2^- \ldots$.

second instance, there are four factors of momentum and the parity is finally odd. In both cases, the amplitude vanishes as p_3 goes to zero in accordance with the earlier argument.

Dalitz's analysis led ultimately to the τ–θ puzzle: were the θ^+ (which decayed into $\pi^+\pi^0$) and τ^+, whose masses and lifetimes were known to be similar, the same particle? Of course this would require them to have the same spin and parity. But the parity of the $\theta^+ \to \pi^+\pi^0$ was necessarily $(-1)^J$ if its spin was J. These values were incompatible with the results for the tau showing that it had J^P in the sequence $0^-, 2^-, \ldots$. How this contradiction was resolved will be seen in Chapter 6.

Cosmic-ray studies had found evidence for hyperons besides the $\Lambda = V_1^0$. Positive particles of a similar mass were observed and initially termed V_1^+ or Λ^+. Evidence for this particle, now called the Σ^+, was observed by Bonetti *et al.* (Ref. 3.8) in photographic emulsion, and by York *et al.* (Ref. 3.9) in a cloud chamber See Figure 3.10. Furthermore, a hyperfragment, which is a Λ or Σ^+ bound in a nucleus, was observed by Danysz and Pniewski in photographic emulsion (Ref.

3.10). See Figure 3.11. Working at Caltech, E. W. Cowan confirmed the existence of a negative hyperon (now called the Ξ^-) that itself decayed into $\Lambda^0\pi^-$ (Ref. 3.11).

By the end of the year 1953, the Cosmotron at Brookhaven National Laboratory was providing pion beams that quickly confirmed the cosmic ray results and extended them. The existence of the V_1^+ (Σ^+) was verified and the V_1^- (Σ^-) was discovered. An especially important result was the observation of four events in which a pair of unstable particles was observed (**Ref. 3.12**). Such events were expected on the basis of theories that Abraham Pais and Murray Gell-Mann developed to explain a fundamental problem posed by the unstable particles. These unstable particles were clearly produced with a large cross section, some percent of the cross section for producing ordinary particles, pions and nucleons. The puzzle was this: The new particles were produced in strong interactions and decayed into strongly interacting particles, but if the decays involved strong interactions, the particle lifetimes should have been ten orders of magnitude less than those observed.

The first step in the resolution was made by Pais, who suggested that the new particles could only be made in pairs. One could assign a multiplicative quantum number, a sort of parity, to each particle, with the pion and nucleon carrying a value $+1$ and the new particles, K, Λ, etc. carrying -1. The product of these numbers was required to be the same in the initial and final state. Thus $\pi^- p \to K^0 \Lambda$ would be allowed, but $\pi^- p \to K^0 n$ would be forbidden. The Cosmotron result on the production of pairs of unstable particles was consistent with Pais' explanation. Pais' parity was to be conserved only in the strong (nuclear) interactions. The weak interactions were not to obey this rule, so weak decays like $\Lambda \to \pi^- p$ were allowed. However, because the weak interactions are quite feeble, the lifetimes of the unstable particles could be much longer than would have been the case if the decays went through the strong interaction.

The associated-production proposal of Pais was only a partial explanation. The full solution was given by Gell-Mann. In Gell-Mann's proposal, the new quantum number that was introduced was not multiplicative, but additive. Each strongly interacting particle has an additive quantum number called *strangeness.* For the old particles (pion and nucleon) the strangeness, S, is 0. For the K^+ the strangeness is $+1$, while for the Λ and Σs it is -1. Pairs of mesons with identical masses but opposite electric charges are antiparticles of each other, just as the positron is the antiparticle of the electron. Each antiparticle is assigned the opposite strangeness from the particle. Thus the K^- has strangeness -1. While Gell-Mann's proposal allowed $\pi^- p \to K^+ \Sigma^-$ but not $\pi^- p \to K^0 n$, just as the scheme of Pais, some of its predictions were different. For example, Gell-Mann's rules forbid $nn \to \Lambda\Lambda$ while Pais' allow it. An especially important distinction was $\pi^- p \to K^- \Sigma^+$. This is forbidden by Gell-Mann's proposal (the final state has strangeness -2) but allowed by that of Pais. Gell-Mann proposed that the

Figure 3.10: An emulsion event with a Σ^+ entering from the left. The decay is $\Sigma^+ \to p\pi^0$. The p is observed to stop after 1255 μm. (Ref. 3.8)

Figure 3.11: The star at A is caused by a cosmic ray (marked p) incident from above colliding with a silver or bromine atom in the emulsion. The track f is due to a nuclear fragment with charge about 5. Its decay at point B shows that it contained a hyperon. The scale at the bottom indicates 50 μm. (Ref. 3.10)

strong interactions conserved isospin and strangeness, and that electromagnetism conserved strangeness, but allowed a unit change of isospin. The weak interactions violated isospin and allowed a unit change of strangeness.

The proposal of Gell-Mann initially met severe opposition. His classification of the particles placed the K meson into two isospin doublets: (K^+, K^0) and $(\overline{K}^0, K^-)$. Two objections were raised: First he was requiring that a neutral meson not be its own antiparticle. Though Kemmer had shown years before that there was nothing wrong with this, it still seemed odd. Moreover, many thought it was impossible to have isodoublet bosons (the Ks) and isovector fermions (the Σs), rather than the better known isodoublet fermions (nucleons) and isovector bosons (the pions). The objections, of course, eventually gave way, as did the resistance to the name strangeness.

The proposal of Gell-Mann was arrived at independently by Nakano and Nishijima. The strangeness S, baryon number B ($B = 1$ for nucleons and the hyperons Λ, Σ, Ξ), the third component of isospin, I_z, and charge, Q, were linked by the Gell-Mann–Nishijima relation,

$$Q = I_z + (B + S)/2$$

Since the masses of the Σ^+ and Σ^- were not close enough to the mass of the Λ for them to form an isotriplet, a new hyperon, Σ^0 was predicted that would decay into Λ and a γ. Since the Ξ^- decayed weakly into $\Lambda\pi^-$ it was assigned $S = -2$. Using the Gell-Mann–Nishijima equation, we see that the Ξ^- must have $I_z = -1/2$. Thus a Ξ^0 with $I_z = 1/2$ is required. These predictions of Gell-Mann were subsequently verified.

In 1954 the Bevatron started operating with proton energies up to 6 GeV at the Radiation Laboratory in Berkeley. The early emulsion work at the Bevatron concentrated on K^+ (that is, θ^+, χ^+, or κ^+) and τ^+ studies. This work considerably augmented the cosmic ray data on mass equality (**Ref. 3.13**, Ref. 3.14) and lifetime equality (Ref. 3.15, 3.16) between the K^+ and the τ^+. If these were different particles, they had to be a very close doublet in mass with very similar lifetimes as well! Subsequent counter experiments at the Bevatron and Cosmotron (Refs. 3.17, 3.18) gave even closer agreement for the lifetimes of the various K decay modes and the tau.

Just as data from accelerators began to supplant those from cosmic rays, a major effort, the G-Stack (for "giant") experiment, was mounted by the groups from Bristol, Milan, and Padua. A volume of 15 liters of emulsion was flown at a height of 27,000 meters for six hours. The emulsion stack was thick enough to stop many of the particles produced by decays at rest. Tracing microscopic tracks through 250 sheets of emulsion was an enormous task, but the reward was also great: the clear identification of the decays $K_{\mu 2}, K_{\pi 2}$ and K_{e3}.

In 1955, W. D. Walker measured two cloud chamber events apparently of the form $\pi^- p \rightarrow K^0 \Lambda$ (Ref. 3.19). One event was consistent with the interpretation that there were no additional unobserved particles. The other, however, was inconsistent with this hypothesis and instead fitted better the supposition that a γ or ν had been produced as well. Walker argued that the best interpretation was that the Λ was a decay product. The deduced mass of the decaying object agreed very well with the known masses of the Σ^+ and Σ^-. It was natural to conclude that the actual process was $\pi^- p \to K^0 \Sigma^0$, followed by $\Sigma^0 \to \Lambda\gamma$. Indeed, Walker showed that that hypothesis explained some discrepancies in the events reported earlier by Fowler *et al.*

The discovery of the Ξ^0 did not take place until 1959. Since the Ξ has strangeness -2, its production by pions is quite infrequent: the minimal process would be $\pi^- p \to K^0 K^0 \Xi^0$. A more effective means is to start with a particle with strangeness -1. This was accomplished by L. Alvarez and co-workers using a hydrogen bubble chamber and a mass-separated beam of K^- mesons of momentum about 1 GeV/c produced by the Bevatron. Using the great analytical power of the bubble chamber technique, they were able to identify an event $K^- p \to K^0 \Xi^0$ (Ref. 3.20). The K^0 decayed into $\pi^+\pi^-$. The Ξ^0 decayed into $\Lambda^0\pi^0$. Both the decay of the K^0 and the decay of the Ξ^0 gave noticeable gaps in the bubble chamber pictures. The Λ^0 was identified by its charged decay mode, $\Lambda \to p\pi^-$. The last hyperon, Ω^-, was not discovered until 1964, as discussed in Chapter 5.

The bubble chamber was invented by Donald Glaser in 1953. The first chambers used propane and other liquid hydrocarbons. The idea was rapidly adapted by Luis Alvarez and his group who used liquid hydrogen (and later also deuterium) as the working liquid. They also developed methods for building increasingly large chambers. The bubble chamber works by producing a superheated liquid by rapid expansion just before (about 10 ms) the arrival of the particles to be studied. Bubbles are formed when boiling starts around the ions produced by the passage of the charge particles through the liquid. These bubbles are allowed to grow for about 2 ms at which time lights are flashed and the bubbles are photographed. The properties of bubble chambers are ideally suited for use with accelerators. At an accelerator, the arrival time of a particle beam is known. This allows one to expand the chamber before the arrival of the charged particles, which is not possible in cosmic ray experiments.

EXERCISES

3.1 Suppose that in an experiment like that of Leprince-Ringuet and L'héritier a singly charged particle of mass $M >> m_e$ scatters elastically from an electron. Let the incident particle's momentum be p and the scattered electron's (relativistic) energy be E. Further, let χ be the angle the electron makes with the incident particle (which is nearly undeflected). Show that

$$M = p\left[\frac{E+m_e}{E-m_e}\cos^2\chi - 1\right]^{1/2}$$

For the event of Leprince-Ringuet and L'héritier, the cloud chamber was in a magnetic field of about 2450 gauss. The incident particle had a radius of curvature of 700 cm while that of the electron was 1.5 cm. Take $\chi = 20^\circ$ and assume the scattering plane was perpendicular to the magnetic field. Estimate M.

3.2 Using the data from Table 1 of Rochester and Butler, Ref. 3.2, and the current values for the π, K, p, and Λ masses, determine whether their photograph 1 is $K^0 \rightarrow \pi^-\pi^+$ or $\Lambda \rightarrow p\pi^-$. Are the errors in the measurements small enough to permit a confident choice?

3.3 Suppose a neutral particle decays into a positive of mass m^+ and a negative of mass m^-. Assume the angular distribution in the initial particle's rest frame is isotropic. Let p_z^+ be the component of the positive particle's momentum along the direction of the incident particle measured in the lab and similarly for p_z^-. Define

$$\alpha = \frac{p_z^+ - p_z^-}{p_z^+ + p_z^-}$$

Show that the points (α, p_t), where p_t is the momentum of a decay product perpendicular to the line of flight of the initial particle, lie on an ellipse. Discuss how this could be used to separate $\Lambda \rightarrow p\pi^-$ from $K^0 \rightarrow \pi^+\pi^-$. See R. W. Thompson in the *Proceedings of the 3rd Rochester Conference.*

3.4 Using the data of Thompson *et al.*, and the mass of the charged pion, determine the mass of the K^0 and the associated uncertainty. Compare with the Q value quoted by these authors.

3.5 Carry out the construction of the Dalitz plot for $\tau \rightarrow 3\pi$. Assume the pions are nonrelativistic with energies E_1, E_2, E_3. Let $M_K - 3M_\pi = Q$ and define $\epsilon_i = E_i/Q$. Construct an equilateral triangle with center $x = 0, y = 0$ and base along $x = -1/3$. Then each side is of length $2/\sqrt{3}$. Now for each point inside the triangle, let ϵ_3 be the distance to the base, ϵ_1 the distance to the right leg of the triangle and ϵ_2 the distance to the left leg. Using the nonrelativistic approximation, show that the physical points lie inside the circle

$$x^2 + y^2 = 1/9$$

Make plots showing the contours of equal probability density for the decay of the τ for the two possibilities, $J^P = 1^-$ and $J^P = 1^+$, using the matrix elements given in the text.

3.6 Consider the decay $K^+ \rightarrow \mu^+\pi^0\nu_\mu$. What is the relation between the energy of the muon in the K^+ rest frame and the invariant mass squared of the $\pi^0 - \nu$ system? What is the maximum energy the muon can have, again in the K rest frame? If the energy of the muon is E, what is the range of energies possible for the π^0? Use this and the relation

$$d\Gamma \sim |\mathcal{M}|^2 dE_1 dE_2$$

to determine the muon energy spectrum assuming the matrix element, $\mathcal{M}$ is constant. Use the result to evaluate the likelihood that the two events discussed by C. O'Ceallaigh, Ref. 3.4, are $K \to \mu^+\pi^0\nu_\mu$. Assume the neutrino, ν_μ, is massless.

BIBLIOGRAPHY

A. Pais gives a first hand account in *Inward Bound*, Oxford University Press, New York,1986.

For a fine historical review, see the articles by C. Peyrou, R. H. Dalitz, M. Gell-Mann and others in *Colloque International sur l'Histoire de la Physique des Particules*, *Journal de Physique*, **48**, supplement au no. 12. Dec. 1982. Les Editions de Physique, Paris, 1982. (In English)

For a clear treatment of much of this material, see S. Gasiorowicz, *Elementary Particle Physics*, Wiley, New York, 1966, Chapters 14 and 15.

Additional coverage is given in D. H. Perkins *Introduction to High Energy Physics*, 3rd Edition, Addison-Wesley, Menlo Park, Calif., 1987, Chapter 4.

REFERENCES

3.1 L. Leprince-Ringuet and M. L'héritier, *Comptes Rendus Acad. Sciences de Paris, séance du 13 Dec. 1944, p. 618* "Existence probable d'une particule de masse 990 $\mathrm{m_e}$ dans le rayonnement cosmique"

3.2 G. D. Rochester and C. C. Butler, "Evidence for the Existence of New Unstable Elementary Particles." *Nature*, **160**, 855 (1947).

3.3 R. Brown, U. Camerini, P. H. Fowler, H. Muirhead, C. F. Powell, and D. M. Ritson, "Observations with Electron-Sensitive Plates Exposed to Cosmic Radiation." *Nature*, **163**, 82 (1949). Only the first page is reproduced here.

3.4 C. O'Ceallaigh, "Masses and Modes of Decay of Heavy Mesons - Part I." *Phil. Mag.*, **XLII**, 1032 (1951).

3.5 R. W. Thompson, A. V. Buskirk, L. R. Etter, C. J. Karzmark and R. H. Rediker, "An Unusual Example of V^0 Decay." *Phys. Rev.*, **90**, 1122 (1953).

3.6 R. Armenteros *et al.*, “The Properties of Charged V Particles.” *Phil. Mag.*, **43**, 597 (1952).

3.7 C. D. Anderson *et al.*, “Cascade Decay of V Particles.” *Phys. Rev.*, **92**, 1089 (1953).

3.8 A. Bonetti, R. Levi Setti, M. Panetti, and G. Tomasini, “On the Existence of Unstable Particles of Hyperprotonic Mass.” *Nuovo Cimento*, **10**, 1 (1953).

3.9 C. M. York, R. B. Leighton, and E. K. Bjornerud, “Direct Experimental Evidence for the Existence of a Heavy Positive V Particle.” *Phys. Rev.*, **90**, 167 (1953).

3.10 M. Danysz and J. Pniewski, “Delayed Disintegration of a Heavy Nuclear Fragment.” *Phil. Mag.*, **44**, 348 (1953).

3.11 E.W. Cowan, “A V-Decay Event with a Heavy Negative Secondary, and Identification of the Secondary V-Decay Event in a Cascade.” *Phys. Rev.*, **94**, 161 (1954).

3.12 W. B. Fowler, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore, “Production of Heavy Unstable Particles by Negative Pions.” *Phys. Rev.*, **93**, 109 (1954).

3.13 R. W. Birge *et al.*, “Bevatron K Mesons.” *Phys. Rev.*, **99**, 329 (1955).

3.14 W. W. Chupp *et al.*, “K meson mass from K-hydrogen scattering event.” *Phys. Rev.*, **99**, 1042 (1955).

3.15 E. L. Iloff *et al.*, “Mean Lifetime of Positive K Mesons.” *Phys. Rev.*, **99**, 1617 (1955).

3.16 L. W. Alvarez and S. Goldhaber, “Lifetime of the τ Meson.” *Nuovo Cimento IV*, **X,2**, 33 (1956).

3.17 L. W. Alvarez *et al.*, “Lifetime of K mesons.” *Phys. Rev.*, **101**, 503 (1956).

3.18 V. Fitch and R. Motley, “Mean Life of K^+ Mesons.” *Phys. Rev.*, **101**, 496 (1956).

3.19 W. D. Walker, “$\Lambda^0 - \theta^0$ Production in $\pi^- p$ Collisions at 1 BeV.” *Phys. Rev.*, **98**, 1407 (1955).

3.20 L. Alvarez *et al.* , “Neutral Cascade Hyperon Event.” *Phys. Rev. Lett.*, **2**, 215 (1959).