Mesons and Hyperons*

G. A. SNOW AND M. M. SHAPIRO

University of Maryland, College Park, Maryland, and
Nucleonics Division, U. S. Naval Research Laboratory, Washington 25, D. C.

A. INTRODUCTION AND NOMENCLATURE

1. Classification of Particles

THE subject of elementary particles is still largely phenomenological. No theory has been completely successful in predicting or explaining the number of different particles that exist, or their intrinsic properties, such as mass, charge, etc. The known elementary particles[1] can be classified into four categories[2]:

(a) *Photons* (γ). These are the quanta of the electromagnetic field. They have zero mass, spin $\hbar$, and they interact exclusively with the charge or current of other particles via the electromagnetic interaction.

(b) *Leptons*. These are relatively light particles of spin $\frac{1}{2}\hbar$ whose interactions with each other and with all other known particles are weak. They include neutrino, ν; antineutrino, $\bar{\nu}$; electron, e^-; positron, e^+; μ^- (negative muon); and μ^+ (positive muon).[3] Strictly speaking, one should distinguish between the leptons ν, e^-, μ^- and the antileptons $\bar{\nu}$, e^+, and μ^+. The leptons appear to obey a conservation law in that a lepton and antilepton are produced or annihilated together. It is also possible, but not established at this time, that there exist two distinct kinds of neutrinos and antineutrinos (95, 110).

(c) *Mesons*. These are unstable, spinless particles that are intermediate in mass between electrons and protons, and that interact strongly with baryons and with each other. There are two families of mesons: pi mesons (π^+, π^0, π^-) and K mesons (K^+, K^0, $\bar{K}^0$, K^-).

(d) *Baryons*. These are strongly interacting particles with spin $\frac{1}{2}\hbar$, at least as massive as protons. They consist of the *nucleons* N (proton p, and neutron n) and the *hyperons* $Y(\Lambda^0$, Σ^+, Σ^0, Σ^-, Ξ^0, and Ξ^- particles). Hyperons are unstable baryons, heavier than protons or neutrons. In addition, theory predicts that corresponding to each baryon there exists an *antibaryon* which has the identical mass and spin of the baryon, but opposite charge. These are called antinucleons $\bar{N}(\bar{p},\bar{n})$ and antihyperons $\bar{Y}(\bar{\Lambda}^0$, $\bar{\Sigma}^+$, $\bar{\Sigma}^0$, $\bar{\Sigma}^-$, $\bar{\Xi}^0$, $\bar{\Xi}^-)$. To date, the existence of the antibaryons $\bar{p}$, $\bar{n}$, $\bar{\Lambda}^0$, and possibly $\bar{\Sigma}^+$ and $\bar{\Sigma}^0$ has been experimentally observed. The baryons and antibaryons obey a stringent conservation law: baryons cannot be created or destroyed except in production or annihilation of baryon-antibaryon pairs. This law is responsible for the stability of nuclei, and hence of matter as we know it.

Besides the conservation of baryons, all reactions that have been observed between elementary particles obey the following strict conservation laws: conservation of energy, momentum, angular momentum, and charge. In addition, all particles with integral spin (in units of $\hbar$) obey Bose-Einstein statistics, hence are called bosons (i.e., γ, π, K), while all particles with half-integral spin obey Fermi-Dirac statistics, hence are called fermions (i.e., ν, e, μ, N, Y, and their antiparticles).

The K mesons and hyperons are called *strange* particles, because of peculiarities in the mechanisms of their production and decay. This aspect is discussed further in Sec. C.

2. Types of Interactions

All the known interactions of the elementary particles other than gravitation appear to fall into three categories:

(a) *Strong interactions*, typified by the virtual processes $N\rightarrow N+\pi$, or $N\rightarrow Y+K$. The strength of these processes may be measured by a dimensionless coupling constant $g^2/\hbar c\sim 1$.

(b) *Electromagnetic interactions*, through which a photon may be virtually emitted or absorbed by any charged particle, real or virtual. The strength of this process is measured by the fine structure constant $\alpha\equiv e^2/\hbar c\sim 1/137$.

(c) *Weak interactions*, typified by the decay processes $n\rightarrow p+e^-+\bar{\nu}$ or $Y\rightarrow n+\pi$. A dimensionless coupling constant that can be used as an appropriate scale factor for these decay processes, is $\sim 10^{-14}$. It is a remarkable fact that almost all of the weak decay processes exhibit a universal coupling constant of the same order of magnitude. Furthermore, it has been experimentally established that in general, parity is not conserved in these weak decay processes. (Parity refers to the symmetry of the wave function describing the state, under the operation of inversion of the spatial coordinate system.)

B. INTRINSIC PROPERTIES OF ELEMENTARY PARTICLES

Table I lists the antiparticle symbol, spin, mass, and mean life of each of the known elementary particles.

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[1] One definition of an "elementary particle" is that it is a particle whose internal structure is not described as a simple compound made up of other particles.

[2] For other general and more complete discussions of the elementary particles see (30, 46, 50, 68, 70, 72, 73, 81, 89, 93, 94, 103, 105, 108, 112–114, 121–124, 141, 143). References in parenthesis appear in numerical order in the Bibliography.

[3] We avoid the usage μ meson, preferring to reserve the term "meson" for the π and K particles discussed in item (c).

TABLE I. Intrinsic properties of elementary particles.[a]

Class	Particle symbol	Antiparticle symbol	Spin in units of $\hbar$	Mass (Mev)	(m_e)	Mean life (sec)
Photon	γ	γ	1	0	0	Stable
	ν	$\bar{\nu}$	$\frac{1}{2}$	0	0	Stable
Leptons	e^-	e^+	$\frac{1}{2}$	0.510976 ± 0.000007[b]	1	Stable
	μ^-	μ^+	$\frac{1}{2}$	105.655 ± 0.010[c]	206.77	$(2.212\pm0.002)\times10^{-6}$ [e]
	π^0	π^0	0	135.00 ± 0.05	264.20	$(1.9\ \pm0.6)\times10^{-16}$ [f]
	π^+	π^-	0	139.59 ± 0.05	273.18	$(2.55\ \pm0.03)\times10^{-8}$
Mesons	K^+	K^-	0	493.9 ± 0.2	966.6	$(1.224\pm0.013)\times10^{-8}$
	K^0	$\bar{K}^0$	0	497.8 ± 0.6	974.2	K_1^0: $(1.00\pm0.04)\times10^{-10}$; K_2^0: $\left(6.1{+1.6 \atop -1.1}\right)\times10^{-8}$
Baryons						
Nucleons	p	$\bar{p}$	$\frac{1}{2}$	938.213 ± 0.01	1836.12	Stable
	n	$\bar{n}$	$\frac{1}{2}$	939.507 ± 0.01[d]	1838.65	$(1.013\pm0.029)\times10^{3}$ [g]
	Λ^0	$\bar{\Lambda}^0$	$\frac{1}{2}$	1115.36 ± 0.14	2182.80	$(2.51\ \pm0.09)\times10^{-10}$
	Σ^+	$\bar{\Sigma}^+$	$\frac{1}{2}$	$1189.4\ \pm0.2$	2327.7	$\left(0.81{+0.06 \atop -0.05}\right)\times10^{-10}$
Hyperons	Σ^0	$\bar{\Sigma}^0$	$\frac{1}{2}$	1191.5 ± 0.5	2331.8	$<0.1\times10^{-10}$
	Σ^-	$\bar{\Sigma}^-$	$\frac{1}{2}$	1196.0 ± 0.3	2340.6	$\left(1.61{+0.10 \atop -0.09}\right)\times10^{-10}$
	Ξ^0	$\bar{\Xi}^0$	$\frac{1}{2}$?	1311 ± 8	2566	$\sim1.5\times10^{-10}$
	Ξ^-	$\bar{\Xi}^-$	$\frac{1}{2}$?	1318.4 ± 1.2	2580.2	$\left(1.3{+0.4 \atop -0.3}\right)\times10^{-10}$

[a] Sources for the data in this table are given either in the following footnotes or in Sec. B. While this table was in preparation, a similar table was being prepared by W. Barkas and A. Rosenfeld for Proc. Ann. Rochester Conf. High Energy Nuclear Phys. 10, 878 (1960), (123). We have benefitted enormously from this work.
[b] E. R. Cohen, K. M. Crowe, and J. W. M. Dumond, Nuovo cimento 5, 541 (1957); *Fundamental Constants of Physics* (Interscience Publishers, Inc., New York, 1957).
[c] See references 51 and 91.
[d] Based on the mass difference $M_n-M_p=1.2939\pm0.0004$, (22).
[e] See references 10, 52, 65, 119, and 137.
[f] Value revised from that given in reference 123. Private communication (78).
[g] See references 88 and 131.

Although this article is concerned with mesons and hyperons, the connection between these and other particles (leptons, nucleons, photons) is close, so a complete list is in order. Where appropriate, a positive, neutral, or negative charge for a particle is denoted by the superscript (+, 0, −), respectively. (The magnitude of the unit of charge is that of the electron.) The charge of an antiparticle is always opposite in sign to that of the particle (e.g., $\bar{K}^+=K^-$). Theoretically, the spin, mass, and mean life of an antiparticle are expected to be equal, respectively, to those of the particle; hence they are listed on the same line in Table I. To date all experiments are consistent with this prediction. Although most of the unstable particles listed in Table I were discovered as products of cosmic-ray interactions,[4] the most precise data derive from experiments with high-energy accelerators, the detectors being bubble and cloud chambers, counters, and photographic emulsions. The values for the masses of the electrons, muons, pions, and nucleons have been taken mainly from the systematic analysis of Cohen, Crowe, and Dumond (Table I, footnote b).

Table II lists the decay modes, Q values (disintegration energies), and branching ratios for π and K mesons. Table III lists the same quantities for the hyperons. The only charged mesons listed in Table II are the positively charged ones (π^+, K^+), since their antiparticles (π^-, K^-) are presumed to have corresponding decay modes and identical Q values and branching ratios. This is consistent with present experimental data. References are given only to a few of the most accurate experiments that bear on the entries in Tables I–III.

[4] For references to this pioneering work see, for example, (128) and Proc. Ann. Rochester Conf. High Energy Nuclear Phys. 2–5 (1952–1955).

1. π Mesons

(a) *Masses*

From momentum-range comparison with protons (12), the masses of π^+ and π^- have been determined, together with the ratio $M_{\pi^+}/M_{\pi^-}=1.0021\pm0.0018$. Other methods of mass determination applying to the π^- meson alone give values in agreement with this. They are based, respectively, on the energy of the γ ray in the reaction $\pi^-+p\rightarrow n+\gamma$ (45), and on the energy of π-mesic x rays (27, 132). The most accurate value is obtained from a combination of the π^+, μ^+ mass difference (33.93±0.05 Mev) (12) with the very accurate new determination of the μ^- mass.

The best mass determinations for π^0 are based on the $\pi^--\pi^0$ mass difference ($M_{\pi^-}-M_{\pi^0}=4.59\pm0.01$ Mev). This has been determined from the Doppler shift or the angular correlation of the decay γ rays from the reactions $\pi^- + p \rightarrow n + \pi^0$ and $\pi^0 \rightarrow 2\gamma$ (32, 116). Most recently and accurately, it has been measured by the determination of the neutron velocity with a time-of-flight method (80).

(b) *Mean Life and Decay Modes*

The π^+ lifetime is most accurately deduced from the time-delay distribution of the decay-product muons emitted by π^+ mesons stopped in a scintillator (9, 31, 85, 90, 142). Since stopping π^- are absorbed in matter, the π^- lifetime can be deduced only from decays in flight (53, 92). $\tau_{\pi^-}/\tau_{\pi^+} = 1.03 \pm 0.11$. π^0 decays are detected by the alternative decay mode $\pi^0 \rightarrow e^- + e^+ + \gamma$, calculated (47) to have a branching ratio of 1.24%. The electron pair arising in this way is called a Dalitz pair. First an upper limit and recently a value for the π^0 lifetime has been deduced from the Dalitz pairs produced in $K_{\pi 2}{}^+$ decay in this way: The distribution in gaps between the $K_{\pi 2}{}^+$ endings and the origin of the electron pair provides a measure of the distribution in life span (78, 82). The branching ratio $(\pi^+ \rightarrow e^+ + \nu)/(\pi^+ \rightarrow \mu^+ + \nu)$ was successfully predicted (15, 64, 87, 134) before its experimental verification (7, 8, 62, 84).

(c) *Spin and Parity*

The spin of the π^+ meson is determined by detailed balance from the reactions $\pi^+ + D \rightleftharpoons p + p$ (29, 35, 54, 125). The π^-, antiparticle of the π^+, is presumed to have equal spin, namely, zero. This spin assignment is consistent with the 100% polarization of the $\mu^\pm$ meson in the decay,

$$\pi^\pm \rightarrow \mu^\pm + \{\nu\bar{\nu}\}.$$

This polarization is possible because parity is not conserved in the decay process. The spin of the π^0 meson must be even since it decays into two γ rays (116, 144). The intrinsic parity of π^0 has been directly shown to be odd by the angular correlation between the planes of electron-positron pairs in the rare decay mode $\pi^0 \rightarrow 2e^- + 2e^+$ (117). (Parity *is* conserved in the purely electromagnetic decays of the π^0.) The parity of the π^- is odd, since the reaction $\pi^- + d \rightarrow n + n$ is observed to occur when π^- mesons are captured from zero orbital angular momentum states (24, 33, 63, 116). Finally, all the strong interactions of π mesons with nucleons are consistent with the theory that describes the π mesons as pseudoscalar particles (spin 0, odd parity) (17, 30, 141). The parity of the π^+ and π^- mesons is only defined relative to the parity of the $(p\bar{n})$ and $(n\bar{p})$ systems, respectively.

TABLE II. Decay modes, branching ratios, and Q values for π and K mesons.[a]

Particle		Decay modes	Q (Mev)	Branching ratio (%)
π^+	$\rightarrow$	$\mu^+ + \nu$	33.93	99.99
		$e^+ + \nu$	139.08	$(1.21 \pm 0.07) \times 10^{-2}$
π^0	$\rightarrow$	$\gamma + \gamma$	135.00	99
K^+	$\rightarrow$	$\mu^+ + \nu (K_{\mu 2})$[b]	388.2	58 ± 2
		$\pi^+ + \pi^0 (K_{\pi 2} \equiv \theta)$	219.3	25.6 ± 2
		$\pi^+ + \pi^+ + \pi^- (\tau)$	75.1	5.7 ± 0.3
		$\pi^+ + \pi^0 + \pi^0 (\tau')$	84.3	1.7 ± 0.3
		$e^+ + \nu + \pi^0 (K_{e3})$	358.4	5.1 ± 0.8
		$\mu^+ + \nu + \pi^0 (K_{\mu 3})$	253.2	3.9 ± 0.5
$K_1{}^0$	$\rightarrow$	$\pi^+ + \pi^-$	218.6	69 ± 3
		$\pi^0 + \pi^0$	227.8	31 ± 3
		$\left\{\begin{matrix} e^\pm \\ \mu^\pm \end{matrix}\right\} + \{\nu, \bar{\nu}\} + \pi^\mp$	$\left\{\begin{matrix} 357.7 \\ 252.6 \end{matrix}\right.$	~ 0.1
$K_2{}^0$	$\rightarrow$	$e^\pm + \{\nu, \bar{\nu}\} + \pi^\mp$	357.7	?[c]
		$\mu^\pm + \{\nu, \bar{\nu}\} + \pi^\mp$	252.6	?[c]
		$\pi^+ + \pi^- + \pi^0$	83.6	$\lesssim 15\%$
		$\pi^0 + \pi^0 + \pi^0$	92.8	?[c]

[a] Additional decay modes involving electromagnetic processes that modify the final number of particles have been systematically omitted from this table; e.g., $\pi^0 \rightarrow e^- + e^+ + \gamma$, or $\pi^+ \rightarrow \mu^+ + \nu + \gamma$. Only the positively charged mesons (π^+, K^+) are listed, since their antiparticles (π^-, K^-) are presumed to have corresponding decay modes, and identical Q values and branching ratios.
[b] The symbols in parentheses are sometimes used as shorthand notation for the decay mode.
[c] Bardon *et al.* (11) observed 152 $K_2{}^0$ decays in a cloud chamber. However, since "strong bias operates in the identification of the π's, μ's, and electrons," reliable branching ratios are as yet unavailable. It is known that the $\pi e \mu$ and $\pi \mu \nu$ modes are "prominent." The $\pi^0 \pi^0 \pi^0$ mode, on the other hand, is extremely difficult to observe and identify.

TABLE III. Decay modes, branching ratios, and Q values for hyperons.

Particle		Decay modes	Q (Mev)	Branching ratio (%)
Λ^0	$\rightarrow$	$p + \pi^-$	37.56	64 ± 3
		$n + \pi^0$	40.85	36 ∓ 3
		$p + e^- + \bar{\nu}$	176.64	~ 0.2
Σ^+	$\rightarrow$	$p + \pi^0$	116.2	50 ± 2[b]
		$n + \pi^+$	110.3	50 ∓ 2
		$p + \gamma$	251.2	~ 0.5
Σ^0	$\rightarrow$	$\Lambda^0 + \gamma$	76.1	100
Σ^-	$\rightarrow$	$n + \pi^-$	116.9	100[c]
Ξ^-	$\rightarrow$	$\Lambda^0 + \pi^-$	63.4	$\sim$100[a]
Ξ^0	$\rightarrow$	$\Lambda^0 + \pi^0$ [a]	60.6	$\sim$100[a]

[a] Since the observation of the Λ^0 is required for the identification of the cascade events, the branching ratio into $(n + \pi^0)$ is unknown.
[b] An upper limit for leptonic decays of Σ^+ is 0.7% (77). Evidence for the decay $\Sigma^+ \rightarrow p + \gamma$ is contained in (118).
[c] An upper limit for leptonic decays of Σ^- is 0.4% (77).

2. *K* Mesons

(a) *Masses*

The most precise determination of the K^+ meson mass is obtained from the Q-value determination of the τ mode of decay, using range-energy relations in nuclear emulsion (16, 79, 83). Other mass determinations that are in excellent agreement are made by range-momentum measurements of K^+ mesons, and from Q-value determinations of the $K_{\mu 2}{}^+$ and $K_{\pi 2}{}^+$ modes of decay (18, 83, 120). Similar but less accurate measurements have been made for the K^- meson. In addition, an accurate mass of the K^- is determined from the reaction

$K^- + p \rightarrow \Sigma^+ + \pi^-$ followed by $\Sigma^+ \rightarrow p + \pi^0$ (55, 60, 135, 140). Experimentally, $M_{K^-}/M_{K^+} = 0.9990 \pm 0.0010$. The K^0 and $\bar{K}^0$ masses are determined from the mass differences $M_{K^-} - M_{\bar{K}^0}$ (126) and $M_{K^+} - M_{K^0}$ (38). The first difference is obtained by using the reaction $K^- + p \rightarrow n + \bar{K}^0$, and the second by comparing the reactions $\pi^- + p \rightarrow \Lambda^0 + K^0$ and $\pi^- + p \rightarrow \Sigma^- + K^+$ in the same π^- beam. The best value for the mass difference between charged and neutral K mesons is -3.9 ± 0.6 Mev (126).

(b) *Mean Life and Decay Modes*

The most accurate K^+ lifetime is determined from the time-delay distributions observed in a counter telescope of the μ^+ and π^+ decay particles from $K_{\mu 2}^+$ and $K_{\pi 2}^+$ decays, respectively (3, 66). The K^- lifetime is measured using K^- disintegrations in flight; it is in excellent agreement with the K^+ lifetime [$\tau_{K^-}/\tau_{K^+} = 0.97 \pm 0.09$ (26)]. The branching ratios of the K^+ meson have been determined from analysis of the disintegrations of K^+ stopping in nuclear emulsion (2, 18, 25, 136). K^0 mesons decay with two distinct lifetimes and so do $\bar{K}^0$. This intriguing phenomenon was predicted by Gell-Mann and Pais (74) using invariance principles and quantum mechanics. The K^0 and its antiparticle the $\bar{K}^0$ can each be considered as a linear combination of two states, called K_1^0 and K_2^0 that have different lifetimes and different decay modes as shown in Table II.[5] In particular

$$K^0 = (K_1^0 + iK_2^0)/\sqrt{2} \quad \text{and} \quad \bar{K}^0 = (K_1^0 - iK_2^0)/\sqrt{2}.$$

The K^0 and $\bar{K}^0$ mesons, being antiparticles of each other, have identical masses, while the K_1^0 and K_2^0 have *slightly* different masses;

$$|M_{K_1^0} - M_{K_2^0}| = (1.0 \pm 0.3) \times 10^{-5} \text{ ev}$$

(21, 28, 107). The lifetime of K_1^0 has been determined from the disintegrations in flight ($K_1^0 \rightarrow \pi^+ + \pi^-$) that follow the reaction $\pi^- + p \rightarrow \Lambda^0 + K^0$ (4, 39, 76, 77). The frequency of the neutral mode of decay, $K_1^0 \rightarrow \pi^0 + \pi^0$, has been determined indirectly, assuming the K^0 to be a 50–50 mixture of K_1^0 and K_2^0 (39). It has also been observed directly in a xenon bubble chamber, where some of the γ rays emitted from the π^0 mesons are detected via the pair-production process (23, 77, 127). No reliable number exists as yet for the branching ratios of the decay modes

$$K_1^0 \rightarrow \left\{ \begin{matrix} \mu^\pm \\ e^\pm \end{matrix} \right\} + \pi^\mp + (\nu, \bar{\nu}),$$

although they are predicted theoretically, and isolated cases of disintegrations of this type have been seen close to the point of production of the K^0 meson (41, 71). The K_2^0 mesons, being much longer lived, are much more difficult to observe. The most accurate lifetime and branching ratios have been obtained by observing K_2^0 disintegrations in a cloud chamber very far from the point of production of K^0 mesons (11). The most accurate statement that can be made about K_2^0 decays is that the disintegration into $\pi^+ + \pi^-$ is not observed. The branching ratios of the various three-body decay modes are only poorly determined.

(c) *Spin and Parity*

The Dalitz analysis of the energy and angular distribution of the pions from τ decay strongly suggests that the spin of the K^+ meson is zero (48, 61). This is supported by the observation of the polarization of the e^+ from positive muons originating in $K_{\mu 2}^+$ decays (37), and from the fact that no asymmetries of the decay products relative to the plane of production of the K^+ meson have ever been observed (121, 122). The K^-, being the antiparticle of K^+, presumably also has spin zero.

The isotropy of the angular distribution of K^0 decays, following the reaction $\pi^- + p \rightarrow \Lambda^0 + K^0$, is also consistent with the hypothesis that the spin of the K^0 is zero (40). Since parity is not conserved in the decay of the K mesons, their intrinsic parity cannot be defined. In fact the existence of both the τ and the $K_{\pi 2}$ modes of decay for the K^+ meson, was the first clue used by Lee and Yang (97) to propose the nonconservation of parity in all weak interactions. The parity of K^- relative to the $(\Lambda^0, \bar{n})$ system can be defined, and experiments indicate that the parity is more likely odd than even (19, 123).

3. Hyperons

(a) *Masses*

The Λ^0 mass is determined most accurately by measuring the Q value for the decay mode $\Lambda^0 \rightarrow p + \pi^-$ in nuclear emulsion (20, 91, 106). The Σ^+ mass is obtained from the Q value of the decay $\Sigma^+ \rightarrow p + \pi^0$, observed at rest in nuclear emulsion (55, 60, 135, 140). The Σ^- mass is determined from the mass difference $M_{\Sigma^-} - M_{\Sigma^+}$ as obtained from a comparison of the hyperon ranges in the two reactions $K^- + p \rightarrow \Sigma^\pm + \pi^\mp$ (34, 55, 60, 135). The Σ^0 mass is determined most accurately from observations in a hydrogen bubble chamber of the spectrum of the Λ^0 hyperons from the decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma$, when the Σ^0's are produced in the reaction $\Sigma^- + p \rightarrow \Sigma^0 + n$ (14). Another method makes use of the reaction $\pi^- + p \rightarrow \Sigma^0 + K^0$ followed by the decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ or $\Sigma^0 \rightarrow \Lambda^0 + e^- + e^+$ (57, 133). The Ξ^- mass is determined from the Q value of the decay $\Xi^- \rightarrow \Lambda^0 + \pi^-$ as observed in a bubble chamber or cloud chamber (13, 67, 130). The Ξ^0 mass is found from the kinematics of the production event $K^- + p \rightarrow \Xi^0 + K^0$ (5).

(b) *Mean Life and Decay Modes*

Many measurements have been made in cloud chambers and bubble chambers of the time distribution

[5] The K_1^0 and K_2^0 particles are eigenstates of the operator CP (charge conjugation $\times$ spatial reflection) with the eigenvalues $+1$ and -1, respectively. See, for example (96).

of $\Lambda^0 \rightarrow p+\pi^-$ disintegrations to yield the Λ^0 mean life (4, 76). Similar but less accurate measurements have been made for $\Sigma^+ \rightarrow p+\pi^0$ and $n+\pi^+$ decays and the $\Sigma^- \rightarrow n+\pi^-$ events (76). The $\Sigma^+ \rightarrow p+\pi^0$ time distribution has also been observed by many groups using nuclear emulsion (56, 60, 69, 77). The experimental observations on the $\Sigma^0 \rightarrow \Lambda^0+\gamma$ decays lead to an upper limit for the Σ^0 mean life of $\sim 10^{-11}$ sec. Theoretically the mean life of the Σ^0 is expected to be $\sim 10^{-19}$ sec, since the Σ^0 decay is purely electromagnetic, and has nothing to do with weak interactions. Recently the mean life of the cascade particle Ξ^- has been determined from high-energy K^- and π^- production events in propane bubble chambers (67, 130). The lifetime of the Ξ^0 has not yet been determined.

The branching ratio $(\Lambda^0 \rightarrow n+\pi^0)/(\Lambda^0 \rightarrow p+\pi^-)$ has been determined indirectly in hydrogen bubble chambers and directly in a xenon bubble chamber from the observations of e^-, e^+ pairs produced by the decay γ rays of the π^0 (23, 39, 77, 127). To date, only two cases have been reported of leptonic decays of the $\Lambda^0(\rightarrow p+e^-+\bar{\nu})$ (42, 111). The Σ^+ branching ratio $(\Sigma^+ \rightarrow n+\pi^+)/(\Sigma^+ \rightarrow p+\pi^0)$ has been observed in nuclear emulsions (with reasonable statistics but an unknown systematic error) (76, 129), and in hydrogen bubble chambers (with more massive statistics and less systematic error) (99). No definite cases of leptonic decay of Σ^+ or Σ^- hyperons have been reported (77, 100). Essentially nothing is known about the branching ratios of Ξ^- since the decay $\Xi^- \rightarrow \Lambda^0+\pi^-$ is used as a signature to identify the Ξ^- hyperon.

Elegant experiments have recently been performed to show that parity is not conserved in the disintegrations $\Sigma^+ \rightarrow p+\pi^0$ (36, 44), as well as in the disintegrations $\Lambda^0 \rightarrow p+\pi^-$ (43, 58).

(c) *Spin and Parity*

The magnitude of the observed up-down asymmetry in the decay of $\Lambda^0 \rightarrow p+\pi^-$ relative to the plane of production (via the reaction $\pi^-+p \rightarrow \Lambda^0+K^0$) has been used to show that the spin of the Λ^0 is $\frac{1}{2}\hbar$ (40, 98). Assuming that the spin of the K^- meson is zero, the reactions $K^-+p \rightarrow \Sigma^\pm+\pi^\mp$, generated by stopped K^- mesons, are used to infer the spins of the Σ^+ and Σ^-. The observed isotropy of the $\Sigma^\pm$ disintegration products implies that the spins of both hyperons are $\frac{1}{2}\hbar$, since the K^- mesons are absorbed from atomic states of zero orbital angular momentum (49, 101, 138). These results agree with data obtained from Λ^0 and Σ decays following the reaction $\pi+n \rightarrow Y+K$, using the Adair analysis (1, 59). All existing data are also consistent with the spin of the Σ^0 being $\frac{1}{2}\hbar$. The Ξ^- and Ξ^0 are known to have half-integral spin, but no direct experimental data exist to prove that their spins are $\frac{1}{2}\hbar$ as is assumed.

Again, since parity is not conserved in hyperon decay, the intrinsic parity of the hyperon is undefined. The relative parities of Σ and Λ^0 or of Ξ and n are physically definable characteristics, but they have not yet been determined.

C. STRANGENESS CLASSIFICATION SCHEME FOR MESONS AND BARYONS

Gell-Mann (75) and Nishijima (109) have introduced a classification scheme for mesons and baryons that has proved extremely useful in codifying selection rules for the domains of strong, electromagnetic and weak interactions. The basic puzzle to which they addressed themselves was the fact that K mesons and hyperons —the "strange particles" [6]—are produced rather copiously through the strong interactions by collisions between π mesons and nucleons; yet they have a very low transition probability for decay back to π mesons and nucleons. Pais first suggested an explanation of this strange situation by postulating the associated production of strange particles (115).

Before describing the Gell-Mann and Nishijima classification scheme, let us review some of the properties of the "ordinary particles." As mentioned in Sec. A, the nucleons obey a stringent selection rule called baryon conservation. If one assigns a *baryon number*, i.e., an integral quantum number $N=+1$ to nucleons, $N=-1$ to antinucleons, and $N=0$ to the π mesons, then baryon conservation can be simply expressed by the selection rule $\Delta N=0$. This rule must hold for all interactions—weak, electromagnetic, and strong. Another important concept for the "ordinary" particles is that of *isotopic spin*. One defines an isotopic spin vector $\mathbf{I}$ having three components analogous to those of an angular momentum vector. The eigenvalues of the operator $(\mathbf{I})^2$ are $I(I+1)$, where I is the total isotopic spin quantum number. The charge state of each type of ordinary particle is related to the third component I_3 of this isotopic spin vector by the relation

$$Q=I_3+\tfrac{1}{2}N \qquad (1)$$

(Q denotes the charge in units of the proton charge). $I_3=+\frac{1}{2}$ and $-\frac{1}{2}$ for proton and neutron, respectively. $I_3=+1$, 0, -1 for π^+, π^0, π^- mesons, respectively. These quantum numbers for antiparticles are obtained from those for the corresponding particles by letting $I_3 \rightarrow -I_3$ and $N \rightarrow -N$. The isotopic spin formalism is useful since the strong interactions conserve total isotopic spin ($\Delta I=0$). This property is called *charge independence* (17, 141). Moreover, since charge is always conserved ($\Delta Q=0$), it follows from Eq. (1) that $\Delta I_3=0$.

The problem is now to include the strange particles in this formalism. Gell-Mann and Nishijima noticed that this can be done by introducing one more quantum number S, the *strangeness number*, into Eq. (1). They generalized Eq. (1) to read

$$Q=I_3+\tfrac{1}{2}N+\tfrac{1}{2}S. \qquad (2)$$

[6] The K mesons and hyperons are called "strange" particles as compared to the "ordinary" particles, the π mesons and nucleons.

TABLE IV. Isotopic spin and strangeness quantum numbers for mesons and baryons.[a] $Q=I_3+\frac{1}{2}(N+S)$. I=total isotopic spin, I_3=3rd component of isotopic spin, S=strangeness quantum number, N=baryon number, and Q=charge.

Mesons	π^+	π^0	π^-	K^+	K^0	$\bar{K}^0$	K^-
I	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
I_3	+1	0	−1	$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$
S ($N=0$)	0	0	0	+1	+1	−1	−1
Baryons	p	n	Λ^0	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
I	$\frac{1}{2}$	$\frac{1}{2}$	0	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$
I_3	$+\frac{1}{2}$	$-\frac{1}{2}$	0	+1	0	−1	$+\frac{1}{2}$	$-\frac{1}{2}$
S ($N=1$)	0	0	−1	−1	−1	−1	−2	−2

[a] Quantum numbers for antibaryons are obtained from those for the corresponding baryons simply by changing the algebraic sign of Q, I_3, N, and S, and leaving I unchanged.

To preserve Eq. (1), one assigns $S=0$ to π mesons and nucleons. The $K(\bar{K})$ mesons are assigned $I=\frac{1}{2}$, $N=0$ and $S=+1(-1)$. The Λ^0 and Σ hyperons have $S=-1$ and $N=+1$, and the cascade hyperons have $S=-2$ and $N=+1$. The isotopic spin, baryon number, and strangeness number assignments for all the mesons and baryons are listed in Table IV. The quantum numbers for antiparticles are obtained from those for particles by letting $N\rightarrow -N$ and $S\rightarrow -S$. Since $Q\rightarrow -Q$, we also have the result $I_3\rightarrow -I_3$. The total isotopic spin quantum number I is the same for a particle and its antiparticle.

The reactions involving mesons and baryons can be simply codified by the following selection rules:

(1) Strong interactions: $\Delta Q=\Delta N=\Delta S=\Delta I=0$.
(2) Electromagnetic interactions: $\Delta Q=\Delta N=\Delta S=0$.
(3) Weak interactions: $\Delta Q=\Delta N=0$; $\Delta S\neq 0$.

The leptons are not included in this classification scheme. They interact only through electromagnetic and weak interactions with all other particles, and the quantum numbers S and I are not assigned to them. As a consequence of these rules, the strong interactions allow, e.g.,

$$\pi^-+p\rightarrow \Lambda^0+K^0, \tag{3}$$

$$\pi^-+p\rightarrow \Sigma^-+K^+, \tag{4}$$

$$\pi^-+p\rightarrow \Xi^-+K^++K^0, \tag{5}$$

but forbid reactions of the type

$$\pi^-+p\rightarrow \Sigma^++K^-, \tag{6}$$

$$N+N\rightarrow \Lambda^0+\Lambda^0, \tag{7}$$

$$\Lambda^0+p\rightarrow n+p. \tag{8}$$

The weak interactions exhibited by the disintegrations listed in Tables II and III, not involving leptons have the property[7] that $\Delta S=\pm 1$. They also are consistent with the selection rule $|\Delta I|=\frac{1}{2}$. For those disintegrations in which a leptonic pair is present in the decay products (e.g., $\Lambda^0\rightarrow p+e^-+\bar{\nu}$), the selection rule $(\delta S/\delta Q)=+1$ appears to hold. (Here δS and δQ denote, respectively, the change in strangeness and in charge of the *strongly interacting particles*. This δQ should not be confused with ΔQ, which always equals zero.) The neutral K mesons, K^0 and $\bar{K}^0$, are distinguished by their strangeness quantum numbers, $S=+1$ and -1, respectively. The $K_1{}^0$ and $K_2{}^0$ neutral mesons, on the other hand, are 50–50 mixtures of K^0 and $\bar{K}^0$ mesons with nonunique strangeness quantum numbers but with unique mean lives, and slightly unequal masses.

The fact that a Λ^0 hyperon and a nucleon cannot transform into two nucleons by strong interaction [Eq. (8)] permits the formation of nuclear compounds consisting of Λ^0 hyperons bound to nuclear matter. These are called hyperfragments, e.g., ${}_\Lambda H^3$ denotes a bound state of Λ^0 and a deuteron. These hyperfragments disintegrate in times characteristic of the weak interactions, that is $\sim 10^{-10}$ sec. No two-body hyperfragments have been observed, but hyperfragments ranging in size from ${}_\Lambda H^3$ up to ${}_\Lambda C^{13}$ have been uniquely identified, and their binding energies determined (6, 102).

[7] Further investigation of the disintegrations of cascade hyperons is needed to test whether all of their decays satisfy $\Delta S=\pm 1$ (in particular, a search for $\Xi\rightarrow n+\pi$ reactions). The disintegration $\Sigma^0\rightarrow\Lambda^0+\gamma$, being purely electromagnetic, conforms to the rule $\Delta S=0$, *not* $\Delta S=\pm 1$.

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