clear Sciences, Brussels, Belgium.

[1]This upper limit of 1% is derived in two ways: (a) In the emulsion data (see reference 5), roughly 20% of the K_{e3}^+ events have electron energies compatible, within measurement errors, with the value of 247 Mev expected for the K_{e2}^+ mode. Since the K_{e3} branching ratio is about 5%, the 1% limit follows. (b) In our own branching-ratio study (see reference 7), the observed small number of electron secondaries unaccompanied by electron pairs from π^0 gamma rays leads to an upper limit of less than 1% for the K_{e2} branching ratio.

[2]R. H. Dalitz, Rend. scuola. internaz. fis. "Enrico Fermi" 11, 298 (1960).

[3]A. Pais and S. Treiman, Phys. Rev. 105, 1616 (1957). In Eq. (1) we have considered only pure couplings.

[4]S. Furuichi, T. Kodama, S. Ogawa, Y. Sugahara, A. Wakasa, and M. Yonezawa, Progr. Theoret. Phys. (Kyoto) 17, 89 (1957).

[5]M. Bruin, D. J. Holthuizen, and B. Jongejans, Nuovo cimento 9, 422 (1958).

[6]D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, Phys. Rev. Letters 7, 255 (1961).

[7]B. P. Roe, D. Sinclair, J. L. Brown, D. A. Glaser, J. A. Kadyk, and G. H. Trilling, Phys. Rev. Letters 7, 346 (1961).

NEW RESONANCES AND STRONG INTERACTION SYMMETRY*

J. J. Sakurai

The Enrico Fermi Institute for Nuclear Studies and the Department of Physics
The University of Chicago, Chicago, Illinois

(Received November 6, 1961)

Two of the most striking mysteries about the multitude of recently discovered resonances are the following:

(1) The branching ratio for Y_1^*,

$$r=[Y_1^*\to(\pi+\Sigma)_{T=1}]/[Y_1^*\to\pi+\Lambda],$$

seems to be anomalously small, and is consistent with zero. The global symmetry model predicts $r=\frac{1}{2}(p_\Sigma/p_\Lambda)^3=11\%$ whereas the experimental ratio[1] is $4\pm4\%$.

(2) The width of the ω^0 meson ($\to\pi^++\pi^-+\pi^0$) is remarkably narrow and consistent with zero. The half-width at half maximum is reported to be less than 12 Mev.[2] (Recall that the total kinetic energy of the decay products is 370 Mev.)

These features once again suggest that there might be a symmetry higher than the symmetry implied by charge independence. We wish to point out that, in a class of theories which are sufficiently symmetric between N and Ξ, it is possible to forbid the $\pi\Sigma$ decay of Y_1^* and make the decay rate for $\omega^0\to\pi^++\pi^-+\pi^0$ vanish to the extent that the $N\Xi$ mass difference could be ignored. Several other consequences of the postulated symmetry are discussed. We also show that the postulated symmetry is a natural consequence of the vector theory of strong interactions provided that N and Ξ (together with Λ and/or Σ) are treated as "fundamental" baryons (not as in the Sakata model).

Let us consider the following discrete operation which we may call hypercharge reflection R.[3]

$$\begin{pmatrix}p\\n\end{pmatrix}\rightleftarrows\begin{pmatrix}\Xi^-\\\Xi^0\end{pmatrix},\quad\begin{pmatrix}\Sigma^+\\\Sigma^0\\\Sigma^-\end{pmatrix}\rightleftarrows\begin{pmatrix}\Sigma^-\\\Sigma^0\\\Sigma^+\end{pmatrix},\quad\Lambda\rightleftarrows\Lambda,$$
$$\begin{pmatrix}\pi^+\\\pi^0\\\pi^-\end{pmatrix}\rightleftarrows\begin{pmatrix}\pi^-\\\pi^0\\\pi^+\end{pmatrix},\quad\begin{pmatrix}K^+\\K^0\end{pmatrix}\rightleftarrows\begin{pmatrix}K^-\\\bar{K}^0\end{pmatrix}. \tag{1}$$

The relative $N\Xi$ parity is assumed to be even, and the spin of the Ξ is assumed to be $\frac{1}{2}$; otherwise speculations given here would be useless. Suppose R is "good" to the extent that the $N\Xi$ mass difference could be ignored. We note that the $\vec{\pi}\cdot(\vec{\bar{\Sigma}}\times\vec{\Sigma})$ interaction, a typical term of which looks like $(\bar{\Sigma}^+\Sigma^+-\bar{\Sigma}^-\Sigma^-)\pi^0$, must vanish. In contrast the $\vec{\pi}\cdot\bar{\Lambda}\vec{\Sigma}$ interaction is fully allowed. Now Y_1^* is known to decay into $\pi+\Lambda$; hence the phenomenological decay interaction $\vec{\pi}\cdot\bar{\Lambda}\vec{Y}_1^*$ must be even under R. This immediately implies that Y_1^* must transform like $\vec{\Sigma}$, and that the phenomenological interaction $\vec{\pi}\cdot(\vec{\bar{\Sigma}}\times\vec{Y}_1^*)$ responsible for $Y_1^*\to\pi+\Sigma$ must vanish.

It also follows that R invariance forbids $\pi+\Lambda\rightleftarrows\pi+\Sigma$, makes the one-pion exchange contribution to $N\Sigma$ forces vanish, and predicts the existence of a $T=\frac{3}{2}$, $p_{3/2}$ $\pi\Xi$ resonance analogous to the πN 3-3 resonance (as in the global symmetry model). The conjectured $\pi\Xi$ resonance may be looked for in

$$K^- + p \to K + \pi + \Xi.$$

Turning now to the ω meson, one readily sees that if ω is even under R, then $\omega^0 \to \pi^+ + \pi^- + \pi^0$ is "forbidden" to the extent that R is good. [To prove this just note that the phenomenological decay interaction $\omega^0 \vec{\pi}^{(1)} \cdot (\vec{\pi}^{(2)} \times \vec{\pi}^{(3)})$ changes its sign under R.] Thus the narrow width of ω^0 would no longer be a mystery.

The electromagnetic couplings of strongly interacting particles are also invariant under R with $A_\mu \to -A_\mu$ since both the third component of the isospin current and the hypercharge current change their signs. The R invariance of the strong and electromagnetic interactions require that both the Λ^0 magnetic moment (currently being measured) and the Σ^0-Λ^0 transition moment be "zero," and that

$$\mu(\Xi^-) = -\mu(p), \quad \mu(\Xi^0) = -\mu(n), \quad \mu(\Sigma^+) = -\mu(\Sigma^-),$$

where μ stands for the anomalous magnetic moment of the baryon in question. [It also leads to $m(\Sigma^+) = m(\Sigma^-)$ in contradiction with experiments, but this disagreement is not too serious.] Our speculation might go even further: Perhaps the weak interactions of strongly interacting particles are also invariant under R. This immediately leads to the relation

$$\alpha(\Xi^- \to \pi^- + \Lambda) = -\alpha(\Lambda \to \pi^- + p)$$

(where α stands for the asymmetry parameter in Ξ^- or Λ decay), which seems to be satisfied within experimental errors.[4]

One might naturally say: All this is very fine. But is there a "deep" reason to believe in invariance under R any more than in global symmetry or in the more restricted doublet symmetry?[5] It has been conjectured that the Yukawa couplings of pseudoscalar mesons to baryons are actually phenomenological manifestations of the interactions of various vector mesons coupled to the appropriate conserved currents of the strong interactions.[6] Suppose N and Ξ (together with Λ and/or Σ) are introduced as "fundamental" particles in the vector theory of strong interactions (VTSI) of reference 6.[7] The fundamental vector couplings then become invariant under R where the charge triplet vector meson ρ coupled to the isospin current transforms as

$$\begin{pmatrix}\rho^+\\ \rho^0\\ \rho^-\end{pmatrix} \to -\begin{pmatrix}\rho^-\\ \rho^0\\ \rho^+\end{pmatrix}, \qquad (2)$$

and the vector meson coupled to the baryonic current (the hypercharge current) is even (odd) under R.[8] In VTSI, π and K must emerge as bound states of baryons and antibaryons. To the extent that R is "good" for the interactions responsible for the existence of π and K, these pseudoscalar mesons must have definite transformation properties under R. Although it does not follow a priori that π and K must transform with "plus" signs as in (1), the alternative choice with "minus" signs would make the $\vec{\pi}\cdot\overline{\Lambda}\vec{\Sigma}$ coupling vanish, which is highly unlikely in view of our knowledge of ΛN forces.[9]

In a recent note[10] it was conjectured that the observed ω of Maglić et al.[2] is the vector meson of VTSI coupled to the baryonic current, and that the 550-Mev peak in the mass plot for $(\pi^+\pi^-\pi^0)$ of Pevsner et al.[2] is the vector meson η coupled to the hypercharge current. With this identification ω must be even under R, and the narrowness of ω follows. R invariance does not explain why η is narrow, but perhaps the smaller phase space available and the weaker $\eta\overline{N}N$ coupling makes it narrow. We can also see that R invariance "forbids" "isoscalar photon" $\to \omega^0$. It is gratifying that a double Clementel-Villi type fit[10] to the isoscalar charge form factor with two poles (at m_η^2 and m_ω^2) does not require too large a value for the residue of the ω pole despite the very strong coupling of ω to $\overline{N}N$. As for the "electromagnetic decays" of ω, note that $\omega^0 \to \pi^0 + \gamma$ and $\omega^0 \to 2\pi^0 + \gamma$ are "forbidden"; $\omega^0 \to \pi^+ + \pi^- + \gamma$ is "allowed" only if the two pions are in an odd relative l state. In contrast, $\eta^0 \to \pi^0 + \gamma$ and $\eta^0 \to 2\pi^0 + \gamma$ are "allowed"; $\eta^0 \to \pi^+ + \pi^- + \gamma$ is "allowed" only if the two pions are in an even relative l state.

So far our statements have been completely independent of the $\Lambda\Sigma$ parity and the dynamical origin of Y_1^*. Since there seems to be some difficulty in interpreting Y_1^* as a resonance of the Dalitz-Tuan type,[11] it is tempting to consider Y_1^* as an object analogous to the 3-3 resonance with even $\Lambda\Sigma$ parity.[12] Amati, Stanghellini, and Vitale[13] emphasized that Y_1^* could emerge as a $p_{3/2}$ $\pi\Lambda$ resonance not only in the global symmetry model but also in a wide class of models in which the $\Lambda\Sigma$ parity is even, and the $\pi\Lambda\Sigma$ coupling is strong. Indeed with

$$f_{\pi\Lambda\Sigma}^2 \approx f_{\pi NN}^2 \gg f_{\pi\Sigma\Sigma}^2 \approx 0,$$

Franklin[14] was able to show (using the Chew-Low type method) that: (1) it is possible to accommodate Y_0^*, Y_1^*, and Y_2^* ($T=2$ resonance sometimes denoted by Z^*) as $p_{3/2}$ resonances; and

(2) $Y_1^* \rightarrow \pi + \Sigma$ is forbidden. Our considerations show that his conclusion (2) can be regarded as a consequence of R invariance which forbids both the $\pi\Sigma\Sigma$ coupling and the $\pi\Sigma Y_1^*$ coupling.

Gell-Mann[3] has considered a unitary symmetry model of strong interactions, commonly called the "eightfold way," in which N, Λ, Σ, and Ξ form an octet. Such a model can also accommodate R invariance in a rather natural manner.[15] Assuming that Y_0^*, Y_1^*, and Y_2^* are all $p_{3/2}$ resonances as in Franklin's theory, we might naturally ask: To what representation of the eightfold way do they belong? The answer is that they belong to a "representation 27" including a $T = \frac{3}{2}$ $K\Sigma$ resonance (which would be the "same thing" as the πN 3-3 resonance in the unitary symmetry limit), a $T = \frac{3}{2}$ $\pi\Xi$ resonance, a $T = 1$ KN resonance (which does not seem to exist[16]), and a host of others.[17] Detailed considerations along this line will appear elsewhere.[18]

It goes without saying that the very existence of a partial symmetry, broken within the realm of the strong interactions, is in manifest contradiction with the idea of Chew and others[19] that all strong interactions are as strong as possible.

---

*Work supported by the U. S. Atomic Energy Commission.

[1]P. Bastien, M. Ferro-Luzzi, and A. H. Rosenfeld, Phys. Rev. Letters 6, 702 (1961), summarize the current experimental data on the Σ/Λ ratio.

[2]B. C. Maglić, L. W. Alvarez, A. H. Rosenfeld, and M. L. Stevenson, Phys. Rev. Letters 7, 178 (1961); N. H. Xuong and G. R. Lynch, Phys. Rev. Letters 7, 327 (1961); A. Pevsner in the Proceedings of the Aix-en-Provence International Conference on Elementary Particles, September, 1961 (to be published); M. L. Stevenson, L. W. Alvarez, B. C. Maglić, and A. H. Rosenfeld, Phys. Rev. (to be published).

[3]This operation is essentially the same as R in M. Gell-Mann, "The Eightfold Way: A Theory of Strong Interaction Symmetry," California Institute of Technology Scientific Laboratory Report CTSL-20 (unpublished). This paper of Gell-Mann should not be confused with his more recent work, "Symmetries of Mesons and Baryons" [Phys. Rev. (to be published)], which makes a much smaller number of "predictions."

[4]W. B. Fowler, R. W. Birge, P. Eberhard, R. Ely, M. L. Good, W. M. Powell, and H. K. Ticho, Phys. Rev. Letters 6, 134 (1961) give $\alpha_\Lambda \alpha_\Xi = -0.65 \pm 0.35$ while the most likely value of α_Λ seems to lie between -0.7 and -0.85 (private communication from R. H. Dalitz based on work of several groups). This disagrees with "weak global symmetry" of S. B. Treiman [Nuovo cimento 15, 916 (1960)] and others which requires $\alpha_\Xi = +\alpha_\Lambda$. More recently, however, A. Pais [Phys. Rev. 122, 317 (1961)] seems to commit himself to only the weaker condition $|\alpha_\Xi| = |\alpha_\Lambda|$.

[5]M. Gell-Mann, Phys. Rev. 106, 1296 (1957); J. Schwinger, Ann. Phys. 2, 407 (1957); A. Pais, Phys. Rev. 110, 574 (1958).

[6]J. J. Sakurai, Ann. Phys. 11, 1 (1960).

[7]We would like to emphasize that R invariance cannot be accommodated in a theory based on the Sakata model in which only p, n, and Λ are "fundamental." In particular the vector meson theory of A. Salam and J. C. Ward [Nuovo cimento 20, 419 (1961)] is not invariant under R.

[8]The R invariance of the vector couplings also holds in the more generalized vector meson theory of Gell-Mann[3] in which a strange vector meson (K^* ?) is coupled to a quasi-conserved strangeness-changing current.

[9]See, e.g., F. Ferrari and L. Fonda, Nuovo cimento 9, 842 (1958); R. H. Dalitz, in Proceedings of the Rutherford Jubilee International Conference at Manchester, September, 1961 (to be published).

[10]J. J. Sakurai, Phys. Rev. Letters 7, 355 (1961).

[11]W. E. Humphrey, Ph.D. thesis, University of California Radiation Laboratory Report UCRL-9752 (unpublished), and R. R. Ross, Ph.D. thesis, University of California Radiation Laboratory Report UCRL-9749 (unpublished). It is a pleasure to thank Professor R. H. Dalitz and Professor S. F. Tuan for enlightening discussions on the interpretations of Y_1^*.

[12]Nearly all arguments in favor of odd $\Lambda\Sigma$ parity given in Y. Nambu and J. J. Sakurai [Phys. Rev. Letters 6, 377 (1961)] are either wrong or obsolete. The author believes that the following parity combination is more likely to be the correct one: $\Lambda\Sigma$ even, $K\Lambda$ odd, and $N\Xi$ even. This agrees with Gell-Mann's eightfold way.[3]

[13]D. Amati, A. Stanghellini, and B. Vitale, Nuovo cimento 13, 1143 (1959); Phys. Rev. Letters 5, 524 (1960).

[14]J. Franklin (to be published).

[15]In Gell-Mann's language,[3] we must consider couplings of pseudoscalar mesons of the "D type." S. Coleman and S. L. Glashow [Phys. Rev. Letters 6, 423 (1961)] show that R invariance in the eightfold way is incompatible with observation. It is easy to see, however, that most statements made in their paper are expected to be accurate only up to a factor of $(m_K/m_\pi)^2 \approx 13$.

[16]Perhaps the exchanges of ρ and η between K and N make the $T = 1$ KN interaction so repulsive (as conjectured in reference 6) that the attraction in the $p_{3/2}$ state due to the Yukawa-type $K\Lambda N$, $K\Sigma N$ couplings gets cancelled to such an extent that no $p_{3/2}$ resonance is possible.

[17]Should most of the $p_{3/2}$ resonances of the representation 27 be observed, we might regard Y_1^* and Y_2^* as "eightfold way resonances" (or "twenty-seven-fold way resonances") rather than as "global symmetry resonances."

[18]S. L. Glashow and J. J. Sakurai, Nuovo cimento (to be published).

[19]G. F. Chew and S. C. Frautschi, Phys. Rev. Letters 5, 580 (1960); Phys. Rev. 123, 1478 (1961).