PHYSICAL REVIEW VOLUME 138, NUMBER 2B 26 APRIL 1965

Observations of Radiative τ^+ Decays*

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(Received 11 December 1964)

Seven examples of the decay mode $K^+ \to \pi^+ + \pi^+ + \pi^- + \gamma$ have been found in a systematic study of 3618 τ^+ decays in nuclear emulsion. The γ energies are 6.3±1.5, 11.4±1.4, 13.4±1.4, 14.2±1.4, 17.8±1.3, 27.5±1.0, and 34.0±0.9 MeV. The experimental branching ratio for γ energies greater than 11 MeV is $P(3\pi+\gamma)/P(3\pi) = (1.7\pm0.7)\times10^{-3}$.

DURING the course of a nuclear-emulsions experiment analyzing 3618 τ^+ decays,[1] seven examples of the radiative τ^+ decay mode, $K^+ \to \pi^+ + \pi^+ + \pi^- + \gamma$, have been identified. The Ilford G5 emulsions were exposed to a 300 MeV/c separated K^+ beam at the Bevatron of the Lawrence Radiation Laboratory of the University of California. The radiative τ's were found as part of a systematic area scanning. The first event identified (No. 2146 in Table I) has already been reported.[2]

For all τ-like stopping K mesons, the plane and dip angles of all secondaries were measured, and secondary tracks were followed until the π^- was identified. (Six obvious decays in flight were not analyzed.) The pion energies were then calculated, using the measured secondary ranges and angles. Since the events are overdetermined, the Q value was calculated as a check. The quantity

$$\phi = \frac{\mathbf{p}_1}{p_1} \cdot \frac{\mathbf{p}_2}{p_2} \times \frac{\mathbf{p}_3}{p_3},$$

where the $\mathbf{p}_i$ are the secondary momenta and the p_i are the corresponding magnitudes, was also calculated for each event. This quantity (an invariant under the choice of numbering of the tracks) is a measure of the coplanarity of the event. If the measured Q differed by more than 5 MeV from the Q value expected for τ decays, or if ϕ differed by more than 0.075 from zero, the event was carefully reinvestigated for possible errors.

The mean Q value for 65 events where all secondary ranges were measured is 74.7 MeV and the standard deviation of the distribution is 1.7 MeV. The expected Q value is 75.11±0.14 MeV.[3] The standard deviation of the Q-value distribution for all events (excluding 35 "incomplete" events where the negative pion secondary could not be identified) is 2.2 MeV. A value of ~3.3 standard deviations below the expected Q value (corresponding to a probability of ~1/2000 if the distribution were Gaussian) was set as a cutoff below which all events were subjected to detailed study. These events (about 15 in number), with apparent Q value less than 68 MeV, were examined for inelastic scattering of secondaries, scattering or interaction of secondaries near the K ending, and secondary or primary decays in flight. Grain counting was carried out when appropriate. Whenever it was found possible to interpret the event in such a way as to make it consistent with an ordinary τ event, it was excluded from further consideration as a radiative τ. Seven events remained.

For each of these seven events, all three secondary tracks ended in the stack. In each case, two secondaries underwent typical $\pi^+ \to \mu^+ \to e^+$ decays at rest, and the third came to rest with or without a visible star. Assuming each event to be an example of the decay mode $K^+ \to \pi^+ + \pi^+ + \pi^- + \gamma$, the γ energy was computed from the pion ranges and the known Q value of τ decay, and the γ momentum was computed from the sum of the pion momenta. The errors on the γ energies were calculated by assuming the same fractional error on the sum of the three pion energies as was found for the distribution of Q values of τ decays when all three secondary ranges were measured. The errors on the γ momenta were calculated by propagating the estimated intrinsic errors in plane angles (±2°), depth measurements (±1μ), emulsion shrinkage factor (±10%), and individual track energies (±3%). (See Table I.) All seven events are consistent with being radiative τ decays. None is consistent with the decay mode $K^+ \to \pi^+ + \pi^+ + \mu^- + \nu$.

It is estimated from the width of the Q-value distribution, and from the examination of the events in the low-energy tail, that the efficiency for identifying radiative τ decays starts to decline for events with γ's of 10–12 MeV and drops rapidly to zero for γ's of still lower energy. (Event No. 567 was identified as a radiative τ only because the charged secondaries visibly fail to conserve momentum.) Hence, the experimental branching ratio for events with γ energies greater than ~11 MeV is $P(3\pi+\gamma)/P(3\pi) = 6/3570 = (1.7\pm0.7)\times10^{-3}$. For the same energy range, Dalitz has calcu-

* Supported in part by grants from the National Science Foundation and by an equipment loan contract with the U. S. Office of Naval Research.
† Supported by a National Aeronautics and Space Administration traineeship.
[1] An analysis of the first 1000 τ^+ decays was reported in T. Huetter, E. L. Koller, S. Taylor, P. Stamer, and J. Grauman, Bull. Am. Phys. Soc. **9**, 23 (1964).
[2] E. L. Koller, S. Taylor, T. Huetter, and P. Stamer, Phys. Rev. **129**, 1381 (1963).
[3] The Q value for the τ and all other particle data were taken from A. Rosenfeld, A. Barbaro-Galtieri, W. Barkas, P. Bastien, J. Kirz, and M. Roos, Rev. Mod. Phys. **36**, 977 (1964).

lated that branching ratio to be 9.5×10^{-4}.[4] The agreement is reasonable.

A total of 5 radiative τ^+ decays have been reported by other experimenters: Daniel and Pal[5] report one event with γ energy 30.2 ± 1.5 MeV; O'Halloran *et al.*[6] report one event with γ energy 32.6 ± 1.0 MeV from ~3000 τ decays; and Puschel *et al.*[7] report three events with γ energies of 14.7 ± 0.5, 10.3 ± 0.6, and 10.5 ± 5.2 MeV from 1389 τ decays.

[4] R. H. Dalitz, Phys. Rev. **99**, 915 (1955).
[5] R. R. Daniel and Yash Pal, Proc. Indian Acad. Sci. **A40**, 114 (1954) and Yash Pal, in *Proceedings of the Fifth Annual Rochester Conference on High-Energy Nuclear Physics* (Interscience Publishers, Inc., New York, 1955).
[6] T. O'Halloran, G. Goldhaber, and S. Goldhaber, Bull. Am. Phys. Soc. **6**, 509 (1961).
[7] W. Puschel, J. Tietge, D. Monti, G. Giacomelli, and A. Quareni Vignudelli, Phys. Letters **2**, 96 (1962).

TABLE I. Data on the radiative τ events. The $T_{i\pm}$ are the energies of the positive and negative secondary pions. E_γ and p_γ are the calculated energy and momentum of the γ. ϕ is the coplanarity measure defined in the text.

Event No.	T_{1+} (MeV)	T_{2+} (MeV)	T_{3-} (MeV)	$\Sigma T_{i\pm}$ (MeV)	$10^2\phi$	E_γ (MeV)	p_γ (MeV/c)
567	4.8	21.6	42.4	68.8	0.66	6.3 ± 1.5	9.1 ± 3.0
1866	13.1	20.5	23.7	57.3	5.6	17.8 ± 1.3	21.4 ± 3.2
1886	5.0	35.3	20.6	60.9	7.1	14.2 ± 1.4	13.0 ± 3.3
1903	3.5	28.5	29.7	61.7	3.4	13.4 ± 1.4	14.6 ± 4.3
1937	16.1	27.3	20.2	63.7	6.2	11.4 ± 1.4	8.6 ± 5.5
2146	9.3	13.8	18.2	41.3	33	34.0 ± 0.9	31.6 ± 1.4
2190	7.6	27.3	12.7	47.6	8.2	27.5 ± 1.0	28.1 ± 4.2

We wish to thank the staff of the Bevatron for making the exposure possible. We also wish to thank our scanning staff, especially D. Moran, G. Taplin, and O. Wayne, for their untiring efforts. We acknowledge, with thanks, the use of the IBM 1620 computer at the Stevens Computer Center.

PHYSICAL REVIEW VOLUME 138, NUMBER 2B 26 APRIL 1965

Parity Conservation and Bootstraps*

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(Received 7 December 1964)

It is suggested that parity conservation in the strong interactions may be a consequence of the bootstrap hypothesis. A model is presented to illustrate how this might come about.

I. INTRODUCTION

IN an earlier epoch, the invariance of interactions under space reflection was, like their invariance under other space-time transformations, "obvious" because the transformation related observers in equivalent inertial frames. The work of Yang and Lee clarified the reliability of such arguments, leaving the true origin of parity conservation in strong and electromagnetic interactions obscure.

We suggest that the invariance of the strong interactions under parity, like isospin invariance and other internal symmetries, be viewed as a dynamical consequece of the bootstrap philosophy. Thus, parity conservation should follow as a consequence of a sufficiently accurate dynamical calculation (since it seems to be valid in nature), rather than be put in as an initial hypothesis. On the other hand, parity nonconservation might well emerge from an inaccurate calculation. To put this suggestion into context, we recall three basic features of the bootstrap philosophy, as they apply to internal symmetries[1]:

(i) There is, first of all, the presumption—or faith—that "dynamics" exists. By dynamics, we mean a set of rules such that, given input data about a physical system, physical consequences can be calculated. The input data consist, presumably, of dimensionless quantities such as the numbers of particles of various spins, the ratios of their masses, interaction coupling constants, and whatever else might be necessary to define the system. The output will include, among other things, an enumeration of the number of bound states produced, their spins, the ratios of their masses, and, in general, other numbers of the same character as the input numbers.

(ii) The bootstrap principle is that the output num-

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

[1] The connection between bootstraps and symmetries has, for example, been discussed by: R. Capps, Phys. Rev. Letters **10**, 312 (1963); R. E. Cutkosky, Phys. Rev. **131**, 1888 (1963); E. Abers, F. Zachariasen, and C. Zemach, *ibid.* **132**, 1831 (1963); M. Baker and S. Glashow *ibid.* **128**, 2462 (1962), Sec. V [remark on the possibility of obtaining parity conservation from a restriction or vector function].