Absolute Distinction between Particles and Antiparticles and CP Violation in $K_{L,S} \to 2\pi$*

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It is shown how interference experiments involving $K_{L,S} \to 2\pi$ can serve to distinguish matter from antimatter in an absolute manner without recourse to any convention.

As is well known, CP invariance requires that there be no *absolute* distinction between particles and antiparticles.[1] This means, for instance, that in a CP-invariant world, until we specify what is meant by a right-handed coordinate system by convention, we cannot communicate to intelligent beings in outer space that our atom is made up of a positively charged nucleus and negatively charged electrons. Even though the now-well-established two-pion decay mode in K_L decay[2] is usually taken as evidence for a breakdown of CP invariance, the mere observation of pion pairs resulting from the long-lived component of a neutral K-particle beam does not, by itself, allow us to distinguish matter from antimatter.[3] In this article we discuss to what extent more sophisticated experiments involving $K_{L,S} \to 2\pi$ violate the principle that no experiment should make an absolute distinction between particles and antiparticles.

Let us first consider an experiment in which we start with a pure beam of K^0 ($\bar{K}^0$) mesons. The beam is allowed to decay in vacuum (i.e., in the absence of a regenerator). In such an experiment the $\pi^+\pi^-$ intensity is given by

$$I=I_0\{\exp(-\gamma_S\tau)+|\eta|^2\exp(-\gamma_L\tau) \pm 2|\eta|\cos(\Delta m\tau-\phi_\eta)\exp[-(\gamma_S+\gamma_L)\tau/2]\}\,, \quad (1)$$

where $\eta=|\eta|\exp(i\phi_\eta)$ denotes the ratio of the amplitudes for $K_L\to\pi^+\pi^-$ and $K_S\to\pi^+\pi^-$, and the upper (lower) sign is appropriate for a beam initially made up of K^0 ($\bar{K}^0$).[4] It is evident that by observing the interference effect represented by the last term of (1), we can tell whether we have started with K^0 or $\bar{K}^0$. Since a pure beam of K^0 ($\bar{K}^0$) could be obtained by charge-exchange scattering of K^+ (K^-) on some target material (regardless of whether the target is made of matter or antimatter), we would have an absolute way of distinguishing positive charges from negative charges.

Experiments of the kind described above have not yet been carried out at this writing. We, therefore, consider a regeneration-interference experiment of the type already performed at CERN and Argonne.[5] When we start with a beam of K_L incident on a regenerator, the $\pi^+\pi^-$ intensity is given by

$$I=I_0\{|\rho|^2\exp(-\gamma_S\tau)+|\eta|^2\exp(-\gamma_L\tau) +2|\rho||\eta|\cos(\Delta m\tau-\phi_\eta+\phi_\rho) \times\exp[-(\gamma_S+\gamma_L)\tau/2]\}\,. \quad (2)$$

For a thin regenerator the phase of the regeneration amplitude ρ is given by[6]

$$\phi_\rho=\arg(if_{21})\,, \quad (3)$$

where

$$f_{21}=f(K^0\mathfrak{N})-f(\bar{K}^0\mathfrak{N})\,, \quad (4)$$

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[1] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957); L. D. Landau, Nucl. Phys. **3**, 127 (1957); E. P. Wigner, Rev. Mod. Phys. **29**, 255 (1957).

[2] J. H. Christensen, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters **13**, 138 (1964); A. Abashian, R. J. Abrams, D. W. Carpenter, G. P. Fisher, B. M. K. Nefkens, and J. H. Smith, *ibid.* **13**, 243 (1964).

[3] In contrast, any positive result in experiments to look for a difference in the partial-decay rates of $\tau^\pm(\tau'^\pm)$ decays or a charge asymmetry in the pion spectra of $\eta\to\pi^+\pi^-\pi^0$ would immediately serve to distinguish particles from antiparticles in an absolute manner.

[4] We are using $|K_S{}^0\rangle\approx 2^{-1/2}(|K^0\rangle+|\bar{K}^0\rangle)$ and $|K_L{}^0\rangle\approx 2^{-1/2}(|K^0\rangle-|\bar{K}^0\rangle)$. The numerical value of ϕ_η depends on this phase convention. Had we used $|K_S{}^0\rangle\approx 2^{-1/2}(|\bar{K}^0\rangle+|K^0\rangle)$ and $|K_L{}^0\rangle\approx 2^{-1/2}(|\bar{K}^0\rangle-|K^0\rangle)$, ϕ_η would have changed to $(\phi_\eta+\pi)$, but the interference term in Eq. (1) also changes sign. Thus there is no observable dependence on this phase convention. In regeneration interference experiments a change of the phase convention changes ϕ_η to $(\phi_\eta+\pi)$ and ϕ_ρ to $(\phi_\rho+\pi)$ so that $(\phi_\eta-\phi_\rho)$ is also invariant to the phase convention.

[5] V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon, Phys. Rev. Letters **15**, 73 (1965); M. Bott-Bodenhausen, X. DeBouard, D. G. Cassel, D. Dekkers, R. Felst, R. Mermod, I. Savin, P. Scharff, M. Vivargent, T. R. Willitts, and K. Winter, Phys. Letters **20**, 212 (1966); **23**, 277 (1966); C. Alff-Steinberger, W. Heuer, K. Kleinknecht, C. Rubbia, A. Scribano, J. Steinberger, M. J. Tannenbaum, and K. Tittel, *ibid.* **20**, 207 (1966); **21**, 595 (1966); C. Rubbia and J. Steinberger, *ibid.* **23**, 167 (1966); A. Firestone, J. K. Kim, L. Lach, J. Sandweiss, H. D. Taft, V. Barnes, H. W. J. Foelsche, T. Morris, Y. Oren, and M. Webster, Phys. Rev. Letters **16**, 556 (1966); R. E. Mischke, A. Abashian, R. J. Abrams, D. W. Carpenter, B. M. K. Nefkens, J. H. Smith, R. C. Thatcher, L. Verhey, and A. Wattenberg, *ibid* **18**, 138 (1967).

[6] For a regenerator of finite thickness Eq. (3) should be modified as

$$\phi_\rho=\arg(if_{21})+\phi_{\Delta m},$$

where $\phi_{\Delta m}$ depends only on the K_L-K_S mass difference, the beam momentum, and the thickness of the regenerator. The main point of our argument is completely unchanged even if we consider a thick regenerator.

with $f(K^0\mathfrak{N})$ [$f(\bar{K}^0\mathfrak{N})$] standing for the forward scattering amplitude of K^0 ($\bar{K}^0$) on nuclei of which the regenerator is made. Let us now consider the case where the K_L beam is incident on a regenerator made of antimatter. The relevant amplitude analogous to (4) can then be written as

$$\begin{aligned}\bar{f}_{21} &= f(K^0\bar{\mathfrak{N}}) - f(\bar{K}^0\bar{\mathfrak{N}}) \\ &= f(\bar{K}^0\mathfrak{N}) - f(K^0\mathfrak{N}) \\ &= -f_{21},\end{aligned} \tag{5}$$

where we have assumed charge-conjugation invariance of the strong interactions.[7] This means that $\bar{f}_{21}$ is 180° out of phase relative to f_{21}.[8] Hence, the last term of (2) changes sign as we replace the regenerator (say, made of copper) by an antiregenerator (made of anticopper).

The experimental results of Ref. 5 indicate that for small values of τ, the amplitude for the two-pion decay of the regenerated K_S interferes constructively with the two-pion decay amplitude of the original K_L beam, the measured values of $(\phi_\eta - \phi_\rho)$ ranging from 1.0 to 1.5 rad under a variety of conditions. In order to find out whether a remote galaxy is made of matter or antimatter, it is sufficient to inquire of the inhabitants of the galaxy whether the interference effect in *their* regeneration-interference experiment starts out being constructive or destructive.

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[7] See, e.g., J. J. Sakurai, *Invariance Principles and Elementary Particles* (Princeton University Press, Princeton, New Jersey, 1964), p. 112.

[8] Actually, even if we relax C invariance of the strong interaction, we can still argue that the phase of $\bar{f}_{21}$ is, in general, different from that of f_{21}.

[9] P. K. Kabir, Nature **213**, 898 (1967).

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Regge Trajectories for Two Yukawa Potentials*

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The leading Regge trajectories generated by two Yukawa potentials of different ranges are studied by both analytical and numerical methods. We find that several new features appear which are not present in the single-Yukawa case. We investigate in detail the behavior of the trajectories as we change gradually from the single- to the two-Yukawa-potential case, paying close attention to the appearance of branch cuts other than the usual right-hand cut in the leading trajectories. We notice that these cuts, if present in relativistic theory, can play important roles in explaining effects such as the polarization in the $\pi^- p$ charge-exchange reaction.

I. INTRODUCTION

ANALYTICAL and numerical methods have been used to investigate extensively Regge trajectories for a single attractive or repulsive Yukawa potential.[1–4] Studies of potential theory have served as one of the main sources of intuition concerning Regge trajectories in strong interaction physics. However, it is extremely unlikely that single attractive or repulsive Yukawa potentials are a good approximation to nuclear forces. Such potentials are unable to model attractive forces with repulsive cores or long-range repulsions; these forces are believed to be important components of the strong interaction.[5]

This paper describes a study of the behavior of Regge trajectories that arise from a superposition of two Yukawa potentials of different ranges. In particular, we shall be interested in the behavior of the trajectories for negative energies, as this is the region which, in the relativistic case, controls the asymptotic behavior of the crossed channel, and thus has direct experimental consequences. Our technique will be to use analytical methods to investigate the features in the weak-coupling limit, and then use numerical solutions of the Schrödinger equation to ascertain which features re-

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[1] A. Amadzadeh, P. G. Burke, and C. Tate, Phys. Rev. **131**, 1315 (1963).

[2] Y. I. Azimov, A. A. Ansel'm, and V. M. Shekhter, Zh. Eskperim. i Teor. Fiz. 44, 361 (1963); 44, 1078 (1963) [English transl.: Soviet Phys.—JETP **17**, 246 (1963); **17**, 726 (1963)].

[3] C. Lovelace and D. Masson, Nuovo Cimento **26**, 472 (1962).

[4] R. G. Newton, *The Complex J-Plane* (W. A. Benjamin, Inc., New York 1964).

[5] M. Moravcsik, *The Two-Nucleon Interaction* (Clarendon Press, Oxford, England, 1963).