L. A. Khalfin. *The instability of the proton and the nonexponetial character of the decay law.*

1. The well-known hypothesis[1] (see also Ref. 2) of violation of the conservation of baryon number has found an interpretation in the grand unification theory (GUT) (see, for example, Ref. 3). This violation leads to new physical effects, namely, proton instability and neutron-antineutron oscillations. They are discussed in this paper from the standpoint of the quantum theory of decay. The unique parameters of the unstable proton and the neutron-antineutron superpositions enable us to investigate subtle effects in the quantum theory of decay[4,5]. By "unique parameters" we mean the anomalously long half-life of the proton ($T_p \approx 10^{30}-10^{33}$ yr) as compared with the time since the Big Bang (of the order of $10^{10}$ yr), and the anomalously low mass difference $\Delta m$ between the neutron-antineutron superpositions as compared with the width $\Gamma_n$, $\Gamma_n/\Delta m \approx 10^3$ of the neutron mass distribution (see, for example, Refs. 3 and 6).

2. The exponential term in the decay law is determined by the pole term in the mass distribution $\omega_p(m)$ of the unstable particle (proton):

$$\omega_p(m)=\omega_p(m)\,[(m-M_p)^{2} \tag{1}$$

and is independent[4,7] of the pole-free (analytic preparation function $\varphi_p(m)$). On the other hand, nonexponential terms in the decay law, which violate homogeneity in time, are found to depend appreciably[4,5] on the preparation function $\varphi_p(m)$ and, consequently, on the origin (creation) of the unstable particle. In 1968, the present author showed[8] that if there exists a finite average value $\overline{m}$ of the mass, then

$$\left.\frac{dz}{dt}\right|_{t=0}=0\ ^{3)},$$

and not $2\Gamma_p$ where $L(t)=|p(t)|^2$ and $p(t)$ is the decay amplitude which is shown by the Fok-Krylov theorem to be related to $\omega_p(m)$ by a Fourier transformation. It follows from this result that the unstable particles are initially $t=0$ stable and the decay law is essentially nonexponential near $t\approx 0$. The estimated size of the interval in which the decay is nonexponential depends on the detailed properties of the mass distribution $\omega_p(m)$ of the unstable particle. Modern theory (GUT) provides only information about the pole term in $[0, t_{ne}]$, so that it will yield only general estimates for $t_{ne}$ based on the mathematical structure of $p(t)$. Estimates such as those reported in this paper are based on the fact that $p(t)$ is the characteristic function from the standpoint of probability theory and that $p(t)$ is the limiting value of a function that is analytic in the half-plane of complex $t$ (Ref. 4). One of the estimates follows from the dispersion sum rule in the quantum theory of decay[4]:

$$\overline{m} \geqslant -\frac{1}{\pi}\int_0^\infty \frac{\ln L(t)}{t^2}\,dt. \tag{2}$$

Examination of such estimates shows that the interval in which the decay is nonexponential is sensitive to the average mass $\overline{m}$ and the variance $\sigma^2$ of the mass distribution, i.e., it is sensitive to the pole-free structure of $\omega_p(m)$. Since the proton is too "young" at the present time $\omega_p(m)$, it is possible that the proton decay law is in fact not exponential at the present. Estimates based on (2) confirm the admissibility of this assumption, which could be of fundamental value in the interpretation of the results of "lifetime experiments"[12] in which a search is made for proton decays. The detection of this nonexponential decay may provide a unique possibility of determining the "preparation function", i.e., the history of the origin of the proton, which is basically impossible if we use only the exponential term in the decay law. A discussion is given of the basic possibility of solving the converse problem of baryon chronology with the view to obtaining information on the earliest stages in the evolution of the inverse.

3. The usual theory of neutron-antineutron oscillations is based on the use of the Weisskopf-Wigner approximation[13]. The most important point is that, in this approximation, the time dependence of the oscillating term is not sensitive to either the violation or conservation of $CP$-invariance by the interaction responsible for the violation of the conservation of the baryon number. It was shown in a recent paper by the present author[14] that if the Weisskopf-Wigner approximation is not used, qualitatively new effects of $CP$-invariance violation occur within the framework of $CP$-noninvariant theory. In particular, the results of Ref. 14 can be used as a basis for showing that, outside the framework of the Weisskopf-Wigner approximation, the time dependence of the oscillating term is sensitive to $CP$-invariance violations. Although this effect is, in general, small, it can be enhanced because of the anomalously high ratio $\Gamma_n/\Delta m \approx 10^3$. The prediction that it may be possible to investigate, in a single experiment, the violation of both the conservation of the baryon number and of $CP$-invariance is important because both these effects are essential in any attempt to explain[1,2] the baryon-antibaryon asymmetry of the universe.

The results summarized in the paper are published in Ref. 15.


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3) This result has been rediscovered in many papers, including papers published quite recently.

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