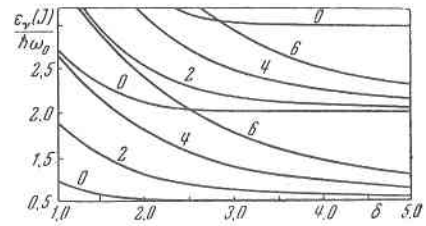
TABLE II

δ	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
$\varepsilon_{1II}/\varepsilon_{1I}$	1.48	1.39	1.36	1.31	1.26	1.21	1.16	1.13	1.11
$\varepsilon_{2I}/\varepsilon_{1I}$	2.17	2.38	2.70	2.87	3.02	3.21	3.27	3.29	3.33
$\varepsilon_{2II}/\varepsilon_{1II}$	1.76	2.16	2.43	2.52	2.94	3.16	3.25	2.27	3.31



it follows from Table II that the moment of inertia I of the nucleus in the second rotational band is less than in the first. This decrease of I is greater for lower values of δ. The quantity a, which determines the coupling of rotational and vibrational states in Eq. (4), is greater in the second rotational band than in the first. Thus if one were to use Eq. (4) to describe collective oscillations, one would need five parameters, rather than the two that are needed to solve (1) with Eq. (3).

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MESONIUM AND ANTIMESONIUM

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GELL-MANN and Pais[1] were the first to point out the interesting consequences which follow from the fact that K^0 and $\tilde{K}^0$ are not identical particles.[2] The possible $K^0 \rightarrow \tilde{K}^0$ transition, which is due to the weak interactions, leads to the necessity of considering neutral K-mesons as a superposition of particles K_1^0 and K_2^0 having a different combined parity.[3] In the present note the question is treated whether there exist other "mixed" neutral particles (not necessarily "elementary") besides the K^0-meson, which differ from their anti-particles and for which the particle → antiparticle transitions are not strictly forbidden.

The laws of conservation of the number baryons and light fermions (or as sometimes called, conservation of nucleon[4] and neutrino[5] charge) strongly limit the number of possible mixed neutral particles. Because of the first-mentioned law mixed particles cannot occur amongst the baryons (e.g. a neutron; a hydrogen atom etc.), and because of the second law such particles cannot exist among the light particles with only one fermion (e.g. neutrino, the systems π^+e^- and π^-e^+, etc.).

From this it evidently follows that besides the K^0-meson the only system consisting of presently-known constituents which could be a mixed particle would be mesonium, defined as the bound system (μ^+e^-). Antimesonium, i.e., the system (μ^-e^+), clearly is different from mesonium and, furthermore, the mesonium → antimesonium inversion is not only not forbidden by any of the known laws, but actually should occur by virtue of already established interactions.

Indeed, the transitions

$$(\mu^+e^-)\rightarrow(\nu+\tilde{\nu})\rightarrow(\mu^-e^+) \tag{1}$$

would be induced by the same interaction that is responsible for the decay of the μ-mesons. The probability $1/\theta$ of the real decay process

$$(\mu^+e^-)\rightarrow\nu+\tilde{\nu}+106.1\text{ Mev}, \tag{2}$$

which can be easily obtained by taking into account the size of the mesonium, is found to be 10^{-4} sec^{-1}, i.e. this probability is 10^{10} times smaller than the usual decay probability of the μ-meson. It is therefore impossible in practice to observe this process which would be indicated by a track corresponding to a stopping μ^+-meson which decays without the emission of a decay electron.

The inversion time, process (1), is proportional to $\hbar/c^2\Delta m$ and is determined[1,6] by the mass difference Δm between the systems symmetrical and antisymmetrical with respect to mesonium and antimesonium. This mass difference is proportional to the first power of the matrix element of the mesonium → antimesonium transition. If this transition is due to a process involving two consecutive transitions, as in (1), Δm is proportional to the square of the coupling constant. The inversion time is then of the order θ and 10^{10} times longer than the half life of the π-meson ($\tau = 2\times10^{-6}$ sec.) The meson half life then determines also the mesonium half life.

However, if one admits a direct $(\mu^+e^-)(\mu^-e^+)$ interaction, then the inversion time T can be very significantly shorter than θ. Indeed, then the mass difference $\Delta m'$ between the symmetric and the antisymmetric system ($\Delta m' \approx 2M/c^2$ where M is the transition matrix element) is proportional to the first power of the coupling constant g. We consequently have:*

$$T\sim\hbar/c^2\Delta m'\sim\hbar/(2g/\pi r^3),$$

where r is the radius of the mesonium. Assuming that the direct interaction $(\mu^+e^-)(\mu^-e^+)$ has the same strength as the other weak interactions, we get $g\approx3\times10^{-49}\text{ erg cm}^3$ and $T\approx5\times10^{-4}$ sec, which is only 300 times longer than τ. Under these conditions it seems at first glance that the mesonium → antimesonium inversion should be observable without too great difficulty. For example, one should see a "fast" negative electron after stopping a μ^+ meson according to the process $(\mu^+e^-)\rightarrow(\mu^-e^+)\rightarrow e_{\text{fast}}+\nu+\tilde{\nu}+e^+$. Unfortunately, however, the inversion mesonium → antimesonium cannot take place inside of matter, owing to the electrical charge asymmetry of the nucleons. This leads to a difference of the mass of mesonium and antimesonium in matter. Furthermore, it should be pointed out that the probability of emission of a fast negative electron (in vacuo) is proportional to $(\tau/T)^2$ and not to (τ/T). Denoting by $\epsilon_{\mu^+}(t)$ and $\epsilon_{\mu^-}(t)$ the probability of finding a mesonium and antimesonium respectively in vacuo at time t if one mesonium "atom" exists at time zero, then

$$\varepsilon_{\mu^+}(t)\sim{}^1\!/_2\,e^{-t/\tau}\left(1+\cos\frac{t}{T}\right),\quad \varepsilon_{\mu^-}(t)\sim{}^1\!/_2\,e^{-t/\tau}\left(1-\cos\frac{t}{T}\right),$$

where the half life of mesonium and antimesonium was assumed to be the same and equal to the μ-meson half life. For these initial conditions the emission probability of a positive and negative electron respectively in vacuo is given by

$$P(e^+)\sim\int_0^\infty\varepsilon_{\mu^+}(t)\frac{dt}{\tau}\sim\frac{1}{2}\left(1+\frac{T^2}{T^2+\tau^2}\right)\sim1,\qquad P(e^-)\sim\int_0^\infty\varepsilon_{\mu^-}(t)\frac{dt}{\tau}\sim\frac{1}{2}\left(1-\frac{T^2}{T^2+\tau^2}\right)\sim\frac{1}{2}\left(\frac{\tau}{T}\right)^2.$$

If there would exist in nature charged particles of long half life with small nuclear interaction, then an effect analogous to the one presently described could be observed. The half life of the particles of mass $\sim500\,m_e$ observed by Alikhanian et al.[8] has not been determined yet; it is merely known to be much greater than 5×10^{-9} sec.

It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and the antineutrino are not identical particles.[9] If the two-component neutrino theory[10] should turn out to be incorrect (which at present seems to be rather improbable) and if the conservation law of neutrino charge would not apply, then in principle neutrino → antineutrino transitions could take place in vacuo. Even in this case, as well as in the case where one assumes that to every world there exists an antiworld, the number of neutrinos and antineutrinos in the universe would have to be the same.

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*The analogous case of the $K^0\rightarrow\tilde{K}^0$ transition to first order in the weak interaction has been treated in detail in Ref. 7.

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ON THE POSSIBILITY OF $\pi\rightarrow e+\nu+\gamma$ DECAY

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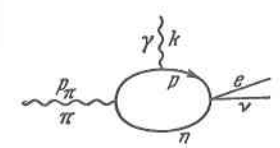
In the presence of the strong interaction of π mesons with nucleons, the decay $\pi\rightarrow e+\nu$ might occur on account of the β-decay interaction, with a lifetime of the same order as that of the decay $\pi\rightarrow\mu+\nu$. In reality, however, the β-decay interaction contains scalar (S) and tensor (T) terms. The decay $\pi\rightarrow e+\nu$ obviously cannot occur on account of the T type term. It may appear that with nonconservation of parity[1] such a decay could take place on account of the S type term, but in reality experiment indicates the presence of the terms not conserving parity in the lepton part of the interaction, whereas for the absence of the $\pi\rightarrow e+\nu$ decay it is sufficient that the heavy particle interaction not contain pseudoscalar terms, since under this condition the nucleon loop reduces to zero.



It seems difficult, however, to explain the absence of the decay $\pi\rightarrow e+\nu+\gamma$. Such a decay can occur on account of the tensor interaction if the virtual nucleon emits the γ-quantum.[4] We estimate the probability of such a process in the first order of perturbation theory in terms of G, where G is the constant of the π-meson-nucleon interaction $G(\tau\Phi_\pi)(\overline{\psi}_N\gamma_5\psi_N)$.

The simplest diagram for the $\pi\rightarrow e+\nu+\gamma$ decay is shown in the figure. With e in rationalized units and $h=c=1$, we get for the matrix element

$$M=g_Te\,(2k\cdot2m_\pi)^{-1/2}\sqrt{2}\;GI_{\epsilon\mu}\,(\bar{\psi}_e\gamma_5\gamma_\epsilon\gamma_\mu\psi_\nu)\,\delta(p_\pi-p_\nu-p_e-k),$$

where $I_{\epsilon\mu}$ is a logarithmically divergent integral over the variables of the virtual nucleons,