from self-consistency requirements, the latter as eigenvalues, in the simplified version even-state energies are taken from experiment or from RPA calculations. In this simplified theory there is no intimation of large diagonal matrix elements.

[13]Of course the method of intermediate coupling as a way of studying the properties of odd nuclei—assuming that one knows the properties of the neighboring even nucleus—has been widely used in several versions since the work of D. C. Choudhury, Kgl. Danske Videnskab Selskab, Mat.-fys. Medd. 28, No. 4 (1954). For a recent application see D. C. Choudhury and E. Kujawski, Phys. Rev. 144, 1013 (1966). A version of the phenomenological theory, more sophisticated in principle, in which allowance is made for a deformation of the 2^+ state as well as for its transition amplitude to the ground state, has been developed by V. K. Thankappan and W. W. True, Phys. Rev. 137, B793 (1965). It is interesting (and was of some inspiration to the present authors) that in a study of the energy levels of Cu^{63}, the best fit was obtained for diagonal and off-diagonal quadrupole matrix elements of Ni^{62} of comparable size. It is our opinion, however, that for a truly accurate description of the one-phonon state and of its parent or daughter odd-nucleus states, one will have to study transitions to states symmetrically disposed with respect to the states of interest and not just transitions to the ground states.

SYMMETRY BETWEEN PARTICLE AND ANTIPARTICLE POPULATIONS IN THE UNIVERSE

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In cosmological theories questions have often been raised as to whether the symmetry property between particles and antiparticles is reflected in the over-all particle and antiparticle populations of the universe.[1] In this Letter we shall show that, according to currently accepted world models and the observed microscopic properties of matter, had the total number of particles and antiparticles been equal at the time when the universe was still in a highly condensed state, all but a small fraction of particle pairs would have annihilated into photons or π mesons as the universe expanded, and the radiation energy density of the present universe would have been much greater than what is observed.[2] A detailed report on the early evolution of the universe will be published elsewhere.

The following conclusion is based on the assumption that sometime in the past the temperature and density of the universe were so high that an equilibrium between particle-pair creation and radiation can be assured. In the case of nucleon pairs this requires a temperature of the order of 10^{12} °K.

In the early epoch of an expanding world model, the radiation energy dominates. For the case of no interaction between radiation and particles, Alpher, Follin, and Herman[3] give the following expressions for the Hubble constant H_0, temperature T, and the particle number density n as functions of the time after creation t:

$$H_0(t) = 1/2t, \tag{1}$$

$$T(t) = T' t^{-1/2}, \tag{2}$$

and, if the total number of particles is conserved,

$$n(t) = n' t^{-3/2}. \tag{3}$$

Different cosmological theories will give somewhat different values of T' and n'. Alpher et al. give $T' = 1.5 \times 10^{10}$ °K. The evaluation of n' is different from the evaluation of T', because the present universe is a matter universe for which

$$T(t) \propto t^{-2/3}, \tag{4}$$

$$n(t) \propto T^3 \propto t^{-2}. \tag{5}$$

Hence n' must be evaluated from the equation

$$n(t) = n'(T/T')^3. \tag{6}$$

Using the present value of $n = 10^{-7}$ and the constant T', one finds that $n' = 10^{22}$, if the age of the universe is taken to be ~10^{10} years. The proper inclusion of interactions between particles and antiparticles will alter only slightly the numerical character of our result.[4]

Using Eqs. (1) and (2), the Boltzmann transport equation describing the nonequilibrium processes in an expanding universe is solved for the case in which (a) the initial particle-pair density is many times greater than the equilibrium pair density, and (b) the transition probability σv for the annihilation process is constant. If the value of the antiparticle density n_- at time t_0 is $n_-^{(0)}$, then the solution for the case in which the numbers of particles and antiparticles are equal is

$$n_+ = n_- = \frac{n_-^{(0)}}{(1+2\sigma v n_-^{(0)} t_0)(t/t_0)^{3/2} - 2\sigma v t_0 n_-^{(0)}(t/t_0)}, \tag{7}$$

and the solutions for the case in which the particle number density n_+ exceeds that for the antiparticles are

$$n_+ - n_- = \Delta n' t^{-3/2},$$
$$n_- = \frac{n_-^{(0)}(t/t_0)^{-3/2}}{[1+n_-^{(0)}t_0^{3/2}/\Delta n']\exp\{(2\Delta n'\sigma v/t_0^{1/2})[1-(t_0/t)^{1/2}]\} - n_-^{(0)}t_0^{3/2}/\Delta n'}, \tag{8}$$

where $\Delta n'$ is a constant. The first equation in Eq. (8) expresses the conservation of baryons [cf. Eq. (3)]. It is easily shown that Eq. (8) reduces to Eq. (7) in the limit $\Delta n' \to 0$. Comparing Eq. (7) with Eq. (3), we see that the pair density is quickly reduced by a depletion factor $1+2t_0/\tau_a$ after a time of the order of t_0 has elapsed, where $\tau_a = [\sigma v n_-^{(0)}]^{-1}$ is the mean lifetime of a particle (or an antiparticle) against annihilation at $t = t_0$. In the case of Eq. (8), however, the depletion factor is

$$1 + \frac{n_-^{(0)} t_0^{3/2}}{\Delta n'} \exp\left(\frac{2\Delta n'\sigma v}{t_0^{1/2}}\right) - \frac{n_-^{(0)} t_0^{3/2}}{\Delta n'},$$

which can be very large if $\Delta n'\sigma v/t_0^{1/2} \gg 1$.

Now we apply Eqs. (7) and (8) to the case of nucleon pairs. First we must find a set of initial density and temperature of the universe at the earliest possible epoch for which the assumptions under which Eqs. (7) and (8) are derived are still valid. We choose $t_0 = 0.01$ sec. The initial temperature and density are then computed from Eqs. (2) and (3): They are 1.5×10^{11} °K and 10^{25}/cm^3, respectively. The equilibrium proton-pair density $n^{(e)}$ is given by

$$n^{(e)} = \frac{\sqrt{\pi}}{4} \frac{m_p^3 c^3}{\pi^2 \hbar^3} \left(\frac{2}{\Phi}\right)^{3/2} e^{-\Phi}$$
$$= 1.2 \times 10^{38} T_{11}^{3/2} \exp(-109/T_{11}),$$
$$T_{11} = T/10^{11}\ ^\circ\mathrm{K}, \tag{9}$$

where

$$\Phi = \frac{m_p c^2}{kT} = \frac{1.09 \times 10^{13}}{T},$$

and m_p is the proton mass. Using Eq. (9) we find that at $T = 1.5 \times 10^{11}$ °K, the equilibrium density $n^{(e)}$ is much less than 10^{25}/cm^3, so that assumption (a) is fulfilled. But this temperature is not very different from that at which the equilibrium density is also 10^{25}/cm^3, on account of the steep temperature dependence of the pair density. The value of σv for p-$\bar{p}$ annihilation at zero energy is a constant and $\sigma v = 2 \times 10^{-15}$ cm^3/sec.[5] We therefore find that, in the case of Eq. (7), the depletion factor $1 + 2t_0/\tau_a$ is of the order of 10^8. Thus, had the universe been created with an equal number of particles and antiparticles, most pairs would have annihilated in the first few hundredths of a second after creation, and the present universe would have been richer in radiation energy than what is observed. Further, unless there is a mechanism, not yet known to us, which can cause a complete separation between particles and antiparticles to take place before the formation of galaxies, an even larger fraction of nucleon pairs will annihilate during galactic and star formation, resulting in a number of 75-MeV photons from the decay of π^0 mesons produced in p-$\bar{p}$ annihilations. Since the present observations exclude such a high-energy flux,[6] we conclude that the assumption of an equal number of particles and antiparticles at the time of creation of the universe is incompatible with both observations and presently accepted physical laws and world models.

If the universe is initially richer in particle population, then Eq. (8) tells us that as long as $\Delta n'\sigma v/t_0^{1/2} \gg 1$, virtually all antiparticles created at the early epoch will have annihilated in the first few hundredths of a second after creation. The present universe is therefore free of any residual antiparticle associated with the creation of the universe. This is consistent with the available data on cosmic-ray antiproton fluxes. The present calculation excludes the presence of antigalaxies.

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[1]R. A. Alpher and R. C. Herman, Science 128, 904 (1958); H. Alfvén and O. Klein, Arkiv Fysik 23, 187 (1962); B. Bonnevier, Arkiv Fysik 27, 305 (1964); H. Alfvén, Rev. Mod. Phys. 37, 652 (1965). The last paper contains the most recent work on a cosmological model based on particle-antiparticle symmetries.

[2]A. A. Penzias and R. W. Wilson, Astrophys. J. 142, 420 (1965); P. G. Roll and D. T. Wilkinson, Phys. Rev. Letters 16, 405 (1966); G. B. Field and J. L. Hitchcock, Phys. Rev. Letters 16, 817 (1966); P. Thaddeus and J. F. Clauser, Phys. Rev. 16, 819 (1966).

[3]R. A. Alpher, J. W. Follin, and R. C. Herman, Phys. Rev. 92, 1347 (1953).

[4]If neutrinos and electron pairs are taken into account, the over-all energy density is a few times greater than the radiation density. See, for example, P. J. E. Peebles, Phys. Rev. Letters 16, 410 (1966).

[5]B. Cork, G. R. Lambertson, O. Piccioni, and W. A. Wenzel, Phys. Rev. 107, 248 (1957).

[6]W. L. Kraushaar and G. W. Clark, Phys. Rev. Letters 8, 106 (1966).

QUARKS AND MAGNETIC POLES*

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It is argued that if the Dirac magnetic monopole has a finite size R, the consequent quantization of charge applies only to the total charge of all particles within a distance R of each other. Then if quarks carry third-integral charge and R is of order of a classical hadron radius, quarks can move freely within hadrons but cannot escape as individuals.

A number of papers that have appeared recently[1] have shown that many experimental observations on baryons and mesons are in remarkably good agreement with a simple additive quark model. This model assumes that quarks and antiquarks interact with each other within hadrons with much the same freedom that nucleons interact with each other within nuclei. There is, however, the striking difference between the two situations that nucleons are quite easily knocked out of nuclei and observed by themselves, whereas individual quarks have thus far not been observed. As pointed out in a recent note,[2] this can be understood if there is a selection principle that has a range built into it. This selection principle would not only require that the over-all baryon number for any system of quarks and antiquarks be an integer, but that the baryon number for each mutually interacting cluster of quarks be an integer. At the same time, the quarks should be able to move rather freely within each cluster, without being greatly inhibited by the selection principle. A model for such a selection principle in terms of many-particle interactions between quarks was proposed[2] and is now being considered in more detail.

The present paper proposes a completely different mechanism for the selection principle. This mechanism requires that the total electric charge of any cluster of particles within a certain small range of each other be an integral multiple of the electronic charge e, although the individual charges need not be. Thus if quarks have third-integral charge, the baryon number of any cluster will be limited to integer values. This mechanism is based on an idea of Dirac[3,4] which relates the value of e to a hypothetical magnetic pole of strength g. Dirac found that the requirement that the phase of the wave function of a particle of charge e be well defined when the gauge associated with the vector potential of the magnetic pole g is transformed, leads to the condition $eg/\hbar c = \frac{1}{2}n$, where n is an integer. On the other hand, Schwinger[4] found that rotation and Lorentz invariance of a quantum field theory of charges and poles interacting with the electromagnetic field demand that $eg/\hbar c$ be an integer, or possibly an even integer. For definiteness, we shall adopt the value $eg/\hbar c = 1$ for the relation between the electronic charge e and the elementary magnetic pole strength g. Then $g = 137e$, and the coupling constant of the pole to the electromagnetic field is $g^2/\hbar c = 137$, in contrast with the coupling constant of an ele-