$N\bar{N}$ interaction and separation of matter and antimatter in the universe

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It is shown that modern theoretical concepts and experimental data on $N\bar{N}$ interaction contradict the Omnes hypothesis concerning the phase transition—the possible mechanism of separation of matter and antimatter during the earlier stages of the creation of the universe.

Omnes[1,2] has advanced the hypothesis that a phase transition can occur in a system consisting of nucleons and antinucleons at a temperature near 300 MeV. This effect, which would be capable of explaining spatial separation of nucleons and antinucleons during the earlier stages of the creation of the universe, follows according to Omnes's statements from the existence of bound $N\bar{N}$ states. We wish to show in this article that certain premises on which the considered scheme is based, as well as the statements contained in[1,2] (and in the review)[3] concerning the character of the $N\bar{N}$ interaction, contradict modern theoretical ideas and the available experimental data. A correct calculation of the bound and resonant $N\bar{N}$ states leads to conclusions that contradict the statements contained in the cited articles.

The effect of separation of nucleons and antinucleons was considered by Omnes within the framework of the following model: (1) The only strongly interacting particles that are in thermodynamic equilibrium are the pions, nucleons, and antinucleons. (2) The $N\bar{N}$ system can form bound states, which include the light mesons (π,η,ρ,ω). The number of mesons is not conserved and is determined from the condition that the free energy be a minimum (in analogy with photons in equilibrium thermal radiation).

The problem is solved using a virial expansion of the free energy F of the system in powers of the density of the nucleons and antinucleons

$$F = F_\pi + F_0(N, T) + F_0(\bar{N}, T) + aT(N+\bar{N}) + bT\frac{N\bar{N}}{V} + b'T\frac{N^2+\bar{N}^2}{V}. \tag{1}$$

Here F_π is the free energy of the mesons and $F_0(N,T)$ is the energy of the ideal nucleon gas. The virial coefficients a, b, and b' take into account the πN, $N\bar{N}$, and NN interactions, respectively.

At a certain temperature, such that

$$b > \frac{1}{4}\left(\frac{2\pi}{mT}\right)^{3/2} e^{1+a+m/T} \tag{2}$$

(m is the nucleon mass), the free-energy minimum corresponds to a solution with two phases, one consisting mainly of baryons and the other of antibaryons.

Omnes's conclusion is that the realization of condition (2) during a certain stage of the evolution of the hot universe is possible.

It is convenient to distinguish between two components b_1 and b_0 of the virial coefficient b. The first is expressed in terms of the S matrix. In the presence of inelastic channels, b_1 satisfies the formula of Dashen, Ma, and Bernstein[4]:

$$b_1 = -8\left(\frac{\pi}{mT}\right)^{3/2} \sum_{I,J} \frac{(2I+1)(2J+1)}{16\pi} \int_0^\infty e^{-E/T} \frac{1}{4i} \langle N\bar{N}/S^{-1}\frac{\overleftrightarrow{\partial}}{\partial E}S/N\bar{N}\rangle dE \tag{4}$$

Here J and I are the spins and isospins of the $N\bar{N}$ system, E is the pair energy in the c.m.s., and

$$S^{-1}\frac{\overleftrightarrow{\partial}}{\partial E}S \equiv S^{-1}\frac{\partial S}{\partial E} - \frac{\partial S^{-1}}{\partial E}S .$$

The term b_0 is the partition function over the bound states of the $N\bar{N}$ system

$$b_0 = -8\left(\frac{\pi}{mT}\right)^{3/2} \sum_n g_n e^{|\epsilon_n|/T} \tag{5}$$

(g_n is a statistical weight and ϵ_n is the binding energy).

The presence of bound states was taken into account in[1,3] in the energy dependence of the S matrix. The sum (5), on the other hand, is separated from the virial coefficient to form the free energy F_π of the pions, whose chemical potential is assumed to be equal to zero.

The fact that in addition to the pions there are also heavy bound $N\bar{N}$ states—mesons with mass on the order of $2m$ (see[5,6])—is not taken into account by Omnes. These mesons are unstable (owing to annihilation) and have lifetimes 10^{-22}—10^{-23} sec (their widths are $\Gamma \approx 10$—100 MeV). Since the lifetimes of these states are certainly lower than or of the order of the relaxation time (we are dealing with times $t \lesssim 10^{-5}$ sec), they can hardly be regarded as independent degrees of freedom in the thermodynamic system. It is obvious that the chemical potential of mesons with approximate mass 2 GeV cannot be regarded as equal to zero at temperatures on the order of 300 MeV. Thus, these bound states should be taken into consideration in the partition function (5).

Further, the energy dependence assumed in[3] for the scattering amplitude that enters directly in b_1 [formula (4)] is incorrect. The author assumes a monotonic decrease of the $N\bar{N}$ scattering phase shifts with energy, an assumption that does not agree with modern data on the $N\bar{N}$ interaction. It is known, in particular, that an important role is played in $N\bar{N}$ scattering by resonant processes. Resonances with widths on the the order of 10—100 MeV were observed, e.g., at total c.m.s. $N\bar{N}$ energies 1900, 1922, 1945, 1970, 2190, 2345, and 2380.[7]

It should also be noted that Omnes confines himself in[3] to allowance for s-waves only. Simple estimates show that waves with orbital angular momenta $l \leqslant 3$ take part at temperatures $T \approx 200$—400 MeV and at a force radius $r \approx 1$ F. The aforementioned resonances correspond to states with $l \neq 0$.[1)]

Obviously, when the virial coefficient is calculated from formula (4) it is necessary to take into account first of all the sharpest (i.e., resonant) dependences of the amplitude in both the elastic and inelastic channels. If we retain in (4), as a first approximation, only the resonant terms, we obtain for b_1 the expression

$$b_1 = -8\left(\frac{\pi}{mT}\right)^{3/2} \sum_{l,J} \frac{(2l+1)(2J+1)}{16\pi} \int_0^\infty e^{-E/T} \frac{\Gamma_{N\bar{N}}/2}{(E-E_0)^2+\Gamma^2/4}\, dE. \qquad (6)$$

Here $\Gamma_{N\bar{N}}$ and Γ are the elastic and total width of the resonance, and E_0 is the resonant energy. As seen from (6), $b_1 < 0$. The term b_0 is also negative. It follows therefore that $b = b_1 + b_0 < 0$ and condition (2) is not satisfied.

It is clear from these estimates that the existing data on the $N\bar{N}$ interaction not only fail to give grounds for an affirmative conclusion of the possible spatial separation of baryons and antibaryons via the mechanism proposed in[3], but lead more readily to the opposite conclusion.

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1)We note also that[3] contains an erroneous statement that the annihilation forces have a supposedly long-range character. Actually the radius of these forces is of the order of the Compton length of the nucleon (i.e., much less than the range of the nuclear interaction—see[5,6,8]).

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