On Nucleon-Antinucleon Symmetry in Cosmology

Abstract. It has been suggested that cosmological models should embody an initial nucleon-antinucleon symmetry and that the present ratio of nucleons to antinucleons is the result of a statistical fluctuation. Simple arguments are presented for evolutionary models which appear to rule out this possibility in the development of the universe.

Recently Goldhaber (*1*) suggested that a correct cosmological model should exhibit particle-antiparticle conjugation symmetry. Indeed there is at present no reason to believe that the laws of nature underlying the universe should yield a preferential role for either particles or antiparticles. Yet there are reasonable arguments presented by Burbidge and Hoyle (*2*) that certainly our galaxy, and probably the presently observable universe, cannot contain more than one antiparticle in 10^7 particles.

These arguments are based on the fact that if the concentration of antiparticles relative to particles were as much as $1:10^7$, then particle-antiparticle annihilation would be sufficient to provide the observed kinetic energy in our galaxy as well as the high-energy electrons involved in radio emission by the Crab nebula and other radio sources. Therefore, if symmetry is demanded, one must seek a cosmological model in which a separation of particles and antiparticles was initially effected or is now being effected in such a way as to explain our not finding an equal influence of matter and antimatter in the observable universe.

On these grounds Goldhaber speculates about initial conditions which are symmetrical between matter and antimatter. He asks the question, "Should we simply assume that nucleons and antinucleons were originally created in pairs, that most nucleons and antinucleons later annihilated each other, and that 'our' cosmos is a part of the universe where nucleons prevailed over antinucleons, the result of a very large statistical fluctuation, compensated by an opposite situation elsewhere?" As still another alternative Goldhaber suggested essentially two "separate universes," one of matter, the other of antimatter, the two being derived from a single initial entity comprising the material of the universe and possessing the desired symmetry.

We should like to point out that one can apparently rule out the possibility that the presently observable universe represents a statistical fluctuation in the history of large-scale nucleon-antinucleon annihilation from an initially symmetric state. The arguments were developed in a paper which we wrote in collaboration with J. W. Follin, Jr., (*3*) some years ago and are presented here in somewhat revised form in the hope of achieving greater clarity.

Suppose that the presently observable expanding universe derived from a state early in the universal expansion in which thermodynamic equilibrium prevailed between nucleons and antinucleons. Consider an ensemble of finite co-moving volume elements V, containing N each of protons, antiprotons, neutrons, and antineutrons (a total of $4N$ particles per volume element V). In order to end up with the largest residual density of matter, we assume that nucleon-antinucleon pair annihilation led first to mesons, which in turn, and later in the universal expansion, led to electron pairs, neutrinos, and radiation, as appropriate. If α be the probability of the reaction leading to mesons, then averaging over the ensemble of finite volume elements should yield $4\alpha N$ as the mean number of particles transmuting to mesons per finite volume element V. The standard deviation of the mean number of nuclei transmuting in this ensemble is therefore

$$\sigma = [4\alpha N(1-\alpha)]^{1/2}$$

This standard deviation clearly has a maximum value for $\alpha = 1/2$, namely,

$$\sigma_{\text{max.}} = N^{1/2}$$

One might argue then that, at best, in any finite volume element V, the excess of nucleons over antinucleons, or the converse, will be of the order of $\sigma_{\text{max.}}$—that is, of the order of $N^{1/2}$.

Assume now that the early history of the expanding universe is that which has been proposed previously (*3*) in connection with synthesis of the elements—namely, the result of a quite general extrapolation back in time of a uniformly expanding relativistic medium. In this model it is supposed that at some early time in the expansion of the universe the temperature was of the order of 10^{10}°K, adequate to support thermodynamic equilibrium among nucleons, antinucleons, and radiation. We ignore other components of the mixture, such as electrons, positrons, neutrinos, and mesons, in these order-of-magnitude arguments. In such a state the number of nucleons and antinucleons should have been of the order of the number of photons. Assuming the radiation field to have been characteristically black-body, one can compute the photon concentration to have been of the order

$$N_\gamma = \left(\frac{kT}{hc}\right)^3 \cong 10^{31}\ \text{cm}^{-3} \text{ at } T = 10^{10}\,°\text{K}$$

In order to be quite conservative, let us consider volume elements V having initially (that is, at $T = 10^{10}$°K) a radius equal to that of the present visible universe ($\sim 6 \times 10^9$ light-years). The number of photons and therefore the total number of particles was roughly $10^{31} \times 10^{84}$, or 10^{115}. For this N, we obtain $\sigma_{\text{max.}} \cong 10^{57}$. In other words, if one considers nucleon-antinucleon evolution from a state of thermodynamic equilibrium at $T = 10^{10}$°K in a volume element as large as the present visible universe, then the maximum excess number of nucleons over antinucleons, or of antinucleons over nucleons, that one might expect from a statistical fluctuation would be of the order of 10^{57}.

This is an absurdly small result from two viewpoints. On the one hand, even ignoring the subsequent dilution by the universal expansion, this number is no more than the number of nucleons in the solar system, which is also $\sim 10^{57}$. On the other hand, it is also considerably less than the maximum of 1 antiparticle in 10^7 particles which could presumably be present in the universe as we know it. In our earlier work (*3*) we used this argument to reinforce our supposition that one had to treat nucleon density in the early stages of the universal expansion as a free parameter and not try to compute it on theoretical grounds. We conclude that one cannot explain the present nucleon-antinucleon asymmetry with a simple argument for a statistical fluctuation without further assumptions.

These arguments do not apply to the other of Goldhaber's speculations—that is, the "cosmon"-"anticosmon" universe. This is a symmetrical form of Lemaître's primeval atom hypothesis, which assumes the evolution of the universe from a single particle, a "universon," containing the mass of the entire universe. With Goldhaber's hypothesis one has the required symmetry to begin with but supposes a separation which removes antimatter from our ken. This model may be philosophically satisfying but must be regarded as considerably more speculative than other cosmological models in vogue, for the reason that it is difficult to imagine observational tests of such a hypothesis at the present time.

RALPH A. ALPHER
General Electric Research Laboratory, Schenectady, New York

ROBERT HERMAN
Research Laboratories, General Motors Corporation, Detroit, Michigan

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