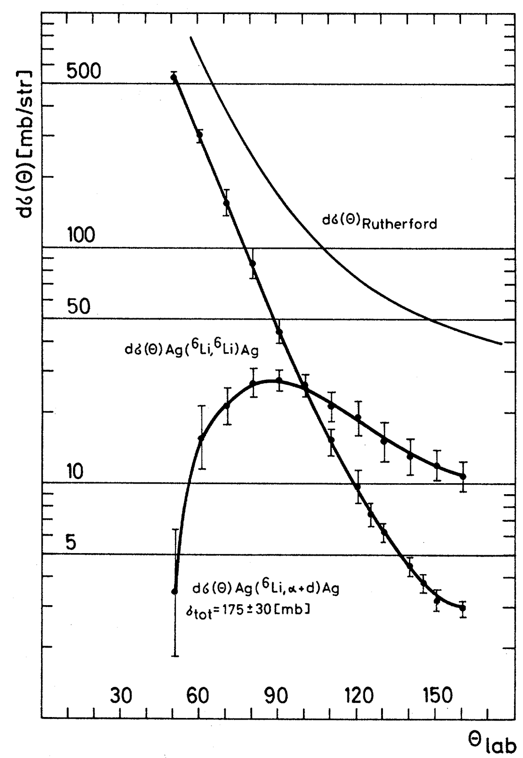

FIG. 2. Angular distribution of α particles from the break-up process of ^{6}Li on silver, angular distribution of elastically scattered ^{6}Li, and the calculated Rutherford cross section. The solid lines through the experimental points are connections only.

as shown earlier by Breit.[2]

The measurements will be extended to an energy range far below the Coulomb barrier to prove the theory on Coulomb break-up, which gives a tool to prove the cluster model of the nucleus.

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MATTER, ANTIMATTER, AND THE ORIGIN OF GALAXIES*

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Baryon inhomogeneities in the early high-density universe may account for the origin of galaxies. Any such inhomogeneity is amplified by baryon-pair annihilation as the universe expands and can eventually result in the formation of galaxies and antigalaxies. This process is more efficient than the usual process which assumes that the initial conditions of a structured universe are density fluctuations.

Symmetry between particles and antiparticles has inspired the suggestion that there is a particle-antiparticle population symmetry and the universe consists equally of matter and antimatter.[1] A major difficulty with this suggestion is the problem of explaining how structures as large as stars or galaxies can form in a particle-antiparticle medium. Furthermore, Chiu[2] shows that as the universe expands only a negligible fraction of the baryons survive pair annihilation. Both these difficulties are overcome if we assume that in the early condensed state of the universe the particle composition is not perfectly homogeneous. It is then possible for separate regions of matter and antimatter to survive and form the foundations of a structured universe.

At very high density the particle-interaction time is short compared with the age of the universe and to a good approximation there is thermal equilibrium.[3] The density n_i of each kind of particle (having a rest mass small in comparison with the mean energy kT) is of the order $(kT/\hbar c)^3$. Hence, in a volume V

$$N_i = Vn_i \sim V(kT/\hbar c)^3. \tag{1}$$

Under these conditions the pressure is close to one third the energy density and we have the adiabatic relation $VT^3 = \text{constant}$, and therefore the N_i are constant.

Let N be the number of baryons and $\overline{N}$ the number of antibaryons in V when the mean energy is large compared with 1 GeV, or $T > 10^{13}$ °K. The compositional inhomogeneity of the baryons is

$$\Delta N/N' = (N-\overline{N})/(N+\overline{N}), \tag{2}$$

where $N' = N+\overline{N}$ is the total number of baryons, $\Delta N = N-\overline{N}$ is the baryon number, and $0 \leqslant |\Delta N/N'| \leqslant 1$. We assume that $\Delta N/N'$ is space varying and that associated fluctuations in mesons and leptons preserve charge neutrality. If, for simplicity, we consider only nucleons, then according to (1) $\Delta N/N'$ persists unchanged while the universe expands until the mean energy drops below ~1 GeV. Nucleon pair annihilation then occurs in the manner discussed by Chiu,[2] and eventually $N+\overline{N} \to \pm\Delta N$. It follows that in an expanding universe

$$\Delta N/N' \to \pm\Delta N/\Delta N = \pm 1. \tag{3}$$

The initial inhomogeneity is therefore amplified during expansion and we are finally left with separate regions of matter and antimatter.

Let $n_0 \sim 10^{-6}$ cm^{-3}, $T_0 \simeq 3$°K be the present mean nucleon density and microwave radiation temperature[4] of the universe. As we go back in time the conserved baryon number n per unit volume increases as T^3 (neglecting losses to pair production) and therefore

$$|\Delta N| = Vn \sim Vn_0(T/T_0)^3. \tag{4}$$

Eventually, at high density when $T > {\sim}10^{13}$ °K, it follows that

$$\Delta N/N' \sim \pm n_0(\hbar c/kT_0)^3, \tag{5}$$

and $|\Delta N/N'| \sim 10^{-9}$ is the maximum required amount of initial baryon inhomogeneity.[5]

The origin of galaxies in an expanding universe poses many perplexing problems, and gravitational theory has so far failed to provide a satisfactory explanation for the existence of such structures.[6] It has been generally supposed that the initial irregularity consists of density fluctuations in a fluid of homogeneous composition. If ρ is the density and $\delta\rho$ the perturbation in density, the contrast density is $\delta\rho/\rho = \delta N'/N'$, or

$$\delta N'/N' = \delta(N+\overline{N})/(N+\overline{N}). \tag{6}$$

It is found that the contrast density grows slowly in an expanding universe and relatively large initial perturbations are necessary to explain the formation of galaxies.

From (6) we see that baryon-pair annihilation during expansion gives

$$\delta N'/N' \to \delta\Delta N/\Delta N, \tag{7}$$

and the contrast density of a fluid of uniform composition, unlike the inhomogeneity (3), is not amplified but remains unchanged. Furthermore, at high density, while the pressure is one third the energy density, $\delta N'/N'$ oscillates at constant amplitude and does not grow with time according to gravitational theory.[7] Eventually, when the density has dropped and $kT < kT_1 \sim 1$ MeV, electron-pair annihilation starts a "radiation deluge" in which the energy density of radiation is large compared with that of matter.[3,8] This period lasts while the density of matter is

$$\rho_1 > \rho > \rho_2,$$

where $\rho_1 \sim \rho_0(T_1/T_0)^3 \sim 10^{-3}$ g cm^{-3}, $\rho_2 = \rho_0{}^4/(aT_0{}^4)^3 \sim 10^{-21}$ g cm^{-3}, $\rho_0 \sim 10^{-30}$ g cm^{-3} is the present mean density, and a is the radiation density constant. During this period the contrast density of the radiation oscillates at constant amplitude, and radiative drag maintains $\delta N'/N'$ also at constant amplitude.[9] Not until $\rho < \rho_2$ and the radiation deluge has subsided can the contrast density at last begin to increase. Under favorable conditions at low pressure we then have[6]

$$\delta N'/N' \propto (\rho_2/\rho)^{1/3}. \tag{8}$$

The mean density of galaxies is $\rho \sim 10^{-24}$ g cm^{-3} and in order that $\delta N' \to N'$ we must have the large initial value of $\delta N'/N' \sim 10^{-1}$. Various types of instability,[10] including radiative cooling mechanisms,[11] can reduce the required amount of initial density irregularity; these instabilities will also enhance the density fluctuations which evolve from inhomogeneities of composition that we have already considered.

Either a compositional irregularity of $\Delta N/N' \sim 10^{-9}$ or a density irregularity of $\delta N'/N' \sim 10^{-1}$ is sufficient for the origin of galaxies. Such large irregularities cannot be explained as statistical fluctuations[3,12] of $|\Delta N/N'| \sim N'^{-1/2}$ for galactic masses of $|\Delta N| \sim 10^{67}$ nucleons (and similarly for $\delta N'/N'$). One possibility is that large fluctuations originate when the universe is at the Planck density[13] of $\rho \sim c^5/G^2\hbar \sim 10^{95}$ g cm^{-3} and classical cosmological theory breaks down. The compositional irregularity is compounded from density fluctuations of component fluids, and although we do not understand the cause of these fluctuations, it seems reasonable to suppose that they are of the same order of magnitude as the over-all density irregularity; that is $\Delta N/N' \sim \delta N/N'$. In any event, if density irregularities are indeed the cause of galaxy formation, a baryon inhomogeneity as small as $\Delta N/N' \sim 10^{-8}\delta N'/N'$ will result in the formation of antigalaxies as well as galaxies.

The idea that the universe consists of structures of matter and antimatter as large as galaxies has raised the objection that it is difficult to see how in the first place matter and antimatter can become separated. A possible answer to this objection has been that in any case we do not understand the processes by which galaxies are formed even in the absence of antimatter. The outlook now, however, is changed and it is difficult to see how galaxies can form without also the formation of antigalaxies. Because baryon inhomogeneity is the more efficient method of producing a differentiated universe we are left with very little reason for believing that the universe does not consist equally of matter and antimatter. Furthermore, using Jeans's criterion or the virial theorem

$$M \sim (kT_2/Gm)^{3/2}/\rho_2^{1/2}, \qquad (9)$$

where m is the nucleon mass, it is seen that at the end of the radiation deluge galactic masses of $M \sim 10^{10}M_\odot$ are gravitationally bound. This result can scarcely apply to a fluid of homogeneous composition because $\delta N'/N'$ still possesses its initial value and has only just begun to increase.

We conclude (i) that baryon inhomogeneities in the early dense universe are likely to be the cause of a differentiated universe, (ii) that, if this is the case, then the differentiation is now in the form of separate structures of matter and antimatter such as galaxies and antigalaxies, and (iii) that in all probability there is a particle-antiparticle population symmetry in the universe. Furthermore, it is quite likely that substructures of antimatter (matter) are present in galaxies (antigalaxies), and the annihilation of these substructures may account for such puzzling objects as exploding galaxies, radio galaxies, and quasistellar sources.

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*Contribution from the Four College Observatories.

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