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EXOTIC RELICS FROM THE BIG BANG

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ABSTRACT

New, exotic (very heavy and/or very weakly interacting) particles would have been produced in the hot, dense environment of the early Universe. If sufficiently long-lived, some exotic relics would have survived to influence the subsequent evolution of the Universe; some may be present today. The laboratory and astrophysical information which can constrain the properties of such new particles is outlined and guidelines are presented for testing models of elementary particle physics.

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1. INTRODUCTION

The high temperature and density achieved during the early evolution of the Universe provided an ideal environment for the production of elementary particles¹⁾. In addition to the known particles, the cosmic accelerator would have produced particles yet to be discovered at conventional accelerators because they are too heavy and/or too weakly interacting. Depending on their properties (mass, lifetime, interaction strength), some of these exotic relics would have emerged from the big bang and influenced the subsequent evolution of the Universe. Those which have avoided annihilation and are sufficiently stable ($\tau \gtrsim t_0 \equiv$ the present age of the Universe $\approx 1-2 \times 10^{10}$ years), will be present today and may be detected by a variety of different techniques. Those which have already decayed but are relatively long-lived ($1 \text{ sec} \lesssim \tau \lesssim t_0$), and those which have annihilated in the recent past, may have left behind some clues to their existence. It is our purpose here to outline the terrestrial experiments and astrophysical observations which may be used to constrain the properties of such exotic new particles. Our work is motivated by, and is an extension of, recent work constraining the properties of heavy hadrons²⁾, specifically those containing sextet quarks³⁾. Our analysis is complementary to the recent discussion of Frampton and Glashow⁴⁾ who concentrated on relics with a very low abundance. Our quantitative results are to be regarded as order of magnitude estimates. In the absence of a very specific particle physics model, and in view of the large astrophysical uncertainties, an attempt at greater numerical precision is hardly justified. Although our analysis here is general some specific constraints do not apply to weakly interacting particles. For an investigation of the limits on heavy neutrinos see Ref. 5).

In order to proceed we must adopt some minimal assumptions regarding the particles in question. It should be clear how these influence our conclusions and how they may be modified. We introduce our three (x two) sets of assumptions by analogy with the production and survival of nucleons⁶⁾ and heavy hadrons²⁾. For a general review of particle production in the early Universe, see Ref. 1).

2. RELIC NUCLEONS AND HEAVY HADRONS

For $T > 1 \text{ GeV}$, the early Universe is a dense soup of quarks, leptons and photons, all comparable in abundance. As the Universe expands and cools, the colour force between quarks becomes strong leading to the formation of colour singlet combinations⁷⁾. The density of these colour singlet objects is initially so large that well-defined hadrons, mostly pions, do not emerge until $T_0 \lesssim 0.2-0.4 \text{ GeV}$. At this stage, the rapid strong and electromagnetic interactions ensure that nucleon-antinucleon pairs are in equilibrium with, and comparable in abundance to, photons. With decreasing temperature, the nucleon

abundance decreases rapidly, and in the absence of any matter-antimatter asymmetry

$$\frac{n_N}{n_\gamma} \approx \frac{n_{\bar{N}}}{n_\gamma} \approx \left(\frac{m_N}{T}\right)^{3/2} \exp\left(-\frac{m_N}{T}\right) \quad (1)$$

At low temperatures ($T \ll m_N$), few new nucleon-antinucleon pairs are produced and few annihilate. The reaction rate $\Gamma = n_N \langle \sigma_{NN} v \rangle$ drops exponentially and becomes negligible compared to the expansion rate $t^{-1} \propto T^2$. There is a critical temperature, T_* , below which no new pairs are produced and none already present annihilate. The surviving ratio of nucleon pairs to photons is ⁶⁾

$$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \approx 10^{-20} \quad (2)$$

This nucleon abundance is some ten orders of magnitude smaller than that observed today ⁸⁾.

The problem, of course, with the above analysis is that baryon symmetry was assumed ($n_N = n_{\bar{N}}$). The Universe, however, is not symmetric ⁸⁾ and the observed baryon asymmetry may have been established by baryon number violating processes in the very early Universe when the temperature was very high ⁹⁾. The observed nucleon-to-photon ratio

$$\frac{n_N}{n_\gamma} \approx 10^{-10} \quad (3)$$

is presumably the remnant of an initial quark asymmetry:

$$n_q - n_{\bar{q}} \approx 10^{-10} (n_q + n_{\bar{q}})$$

In the context of grand unified theories it is not unreasonable to expect that the same processes which led to baryon asymmetry could also have produced a particle-antiparticle asymmetry of similar magnitude for the new, exotic particles under consideration here. In that case, the abundance (we will make all comparisons with nucleons) could be $f = n/n_N \approx 0(1)$. However, for the same reasons that estimates of nucleon asymmetry are very sensitive to details of the calculations, large variations from $f \approx 1$ are possible ¹⁰⁾. Such relics would be very common; their absence will lead to significant constraints.

As another, more exotic, example of relics from the big bang, Dover et al. ²⁾ have discussed the survival of hadrons containing heavy quarks (Q). For $m_Q \gtrsim 10$ GeV, the $Q\bar{Q}$ abundance (again assuming symmetry; otherwise $f \approx 1$) freezes

out before quarks are confined in hadrons ($T_* > T_c \approx 0.2-0.4$ GeV). If the heavy hadrons are formed from Q and two ordinary (colour triplet) light quarks (or antiquarks) q , the resulting hadron will have "normal" strong interactions. In particular, the annihilation cross-section could be comparable to the $N\bar{N}$ annihilation cross-section. In that case when the temperature drops below T_c , the heavy hadrons (and antihadrons) formed by confinement begin annihilating²⁾. At this stage $T < T_c \ll m_Q$, and no new heavy hadron pairs are produced. The surviving abundance of heavy hadrons, therefore, depends only on the $N\bar{N}$ annihilation cross-section and not, for example, on m_Q (provided that $m_Q \gtrsim 10$ GeV²⁾, and one sees from Eqs (2) and (3) that

$$f = \frac{n}{n_N} \approx 10^{-10} \quad (4)$$

Any particle whose annihilation cross-section is smaller than $\sigma_{N\bar{N}}$ will "freeze-out" at a higher abundance (see, e.g., Ref. 1)). Equation (4), therefore, represents a reasonable lower limit to the abundance of exotic relics (i.e.: $f \gtrsim 10^{-10}$). We note that the analysis of Frampton and Glashow⁴⁾ is, in this respect, complementary to ours in that they were mainly concerned with $f \lesssim 10^{-10}$.

One other possibility presents itself. Suppose the exotic particle in question does not bind with ordinary quarks at confinement. In this case there will be no renewed annihilation below T_c and the abundance will be determined by the competing processes at freeze-out ($T_* \propto M$). Suppose the interactions are of a gauge type so that the low-energy ($T_* \ll M$) annihilation cross-section is in order of magnitude

$$\langle \sigma_{ann} v \rangle \approx \frac{\alpha^2}{M^2} \quad (5)$$

This is quite a conservative estimate, in that many recently popular models¹¹⁾ have heavy particles with gauge coupling strengths $O(1) \gg \alpha$ at $T \approx M$. Assuming (5), the surviving abundance relative to nucleons is¹⁾

$$f = \left(\frac{n}{n_N} \right) \approx 10^{-10} \left(\frac{M_N \langle \sigma_{n\bar{n}} v \rangle}{m \langle \sigma_{ann} v \rangle} \right) \approx 10^{-6} \left(\frac{m}{M_N} \right) \quad (6)$$

Since we will be concerned with $M \gtrsim 10 M_N$, this case is intermediate between the asymmetric case ($f \approx 1$) and the nuclear case ($f \approx 10^{-10}$). If the annihilation cross-section were $O(1/M^2)$, then the quantity f would become four orders of magnitude smaller than in Eq. (6), but still be intermediate between the asymmetric and nuclear cases.

When a new particle is proposed, it will be possible, of course, to calculate its big bang production and its surviving abundance¹⁾. In the absence of specific examples we illustrate our approach with three examples which have some physical justification as discussed above, and which may be expected to span the range of interest.

$$\text{Asymmetric} : f \approx 1 \quad (7a)$$

$$\text{Symmetric} : f \approx 10^{-6} \left(\frac{m}{m_N} \right) \quad (7b)$$

$$\text{Symmetric} : f \approx 10^{-10} \quad (7c)$$

3. EXOTIC PARTICLE LIFETIMES

Very short-lived particles ($\tau \leq 1$ second) will leave few clues to their existence. Longer lived particles ($1 \text{ sec} \leq \tau \leq t_0$) may have had sufficient influence on the evolution of the Universe so as to signal their fleeting existence. Long-lived or stable particles ($\tau \geq t_0$) are present today and may be searched for by direct or indirect means. It is essential, therefore, before proceeding further, to make some assumptions about the stability of the new, exotic particle.

Here, too, we use the nucleon analogy. It is reasonable to assume that decay is mediated by a relatively heavy ($\gg M_N, M_W(?)$) boson whose mass M_B may be compared to M_X the mass of the proton-decay-mediating boson (for numerical estimates it will be assumed that $M \approx 10^{14\frac{1}{2}} \text{ GeV}^{12}$). For a "second order" decay of the type indicated in Fig. 1a, the lifetime may be expected to scale relative to that of the nucleon as

$$\frac{\tau}{\tau_N} \approx \left(\frac{m_B}{m_X} \right)^4 \left(\frac{m_N}{m} \right)^5 \quad (8)$$

as long as $M_B \gg M$. The proton lifetime is estimated to be¹²⁾ $\tau_N \approx 10^{30 \pm 2} \text{ yr}$ and in our estimate we will take $\tau_N \approx 10^{30} \text{ yr}$. (Note that if $M_B \lesssim M$ then the heavy particle may decay in first order: in this case its lifetime would be too short to leave clues to its existence.)

Selection rules may forbid a second-order decay. A two-stage "fourth-order" decay of the type indicated in Fig. 1b would probably have a lifetime which scales as $\tau \propto M_B^8 M^{-9}$ for $M \ll M_B$, so that

$$\left(\frac{\tau}{\tau_N} \right) \approx \left(\frac{m_X}{m_N} \right)^4 \left(\left(\frac{m_B}{m_X} \right)^8 \left(\frac{m_N}{m} \right)^9 \right) \approx 10^{58} \left(\frac{m_B}{m_X} \right)^8 \left(\frac{m_N}{m} \right)^9 \quad (9)$$

Since extension to higher order decays is straightforward, we limit our discussion to the two cases (8) and (9).

Since accelerator searches have failed to reveal new, relatively stable particles with $M \lesssim 10 M_N^{13)}$, we restrict our attention to $M \gtrsim 10 M_N$.

4. CONSTRAINTS ON LONG-LIVED PARTICLES

There are terrestrial and astrophysical data constraining the properties (M, τ, f) of long-lived ($\tau > t_0$) relics. A major uncertainty in interpreting the data relates to the present distribution of the relics. If, for example, the relics were sufficiently decoupled from ordinary matter, they may have avoided collapsing along with nucleons in the course of forming stars and planetary systems (e.g., the solar system). Terrestrial searches could set no limits on such weak interacting particles^{*)}. Thus the absence of terrestrial evidence for relics is not evidence of absence.

For symmetric relics, annihilation ceased in the early Universe when the density became so low that the annihilation rate dropped below the expansion rate. During recent epochs, however, inhomogeneities in a basically smooth Universe are enhanced to form galaxies, stars, etc. Annihilation would have begun anew in these density enhancements and could have eliminated virtually all of the (symmetric) relics which survived the big bang. The fate of symmetric relics, therefore, depends crucially on whether they are shielded from annihilation by, for example, having been incorporated in nuclei. Although relics which have annihilated during recent epochs could not be detected terrestrially, their annihilation radiation would offer a clue to their previous existence. With these caveats in mind, let us turn to specific constraints.

i) Too much mass in the Universe? Nucleons may account for all of the mass in the Universe. However, because of the "missing light" problem that on larger scales $\gtrsim$ galaxies more of the mass is non-luminous, it is possible that nucleons do not dominate the total mass density ρ , but it is difficult to estimate the fraction in non-nucleonic matter such as relic neutrinos. However, the data on X-ray emission from clusters of galaxies suggest that $\rho \lesssim 10 \rho_N^{14)}$. To avoid too much mass in exotic relics we need

$$f \leq 10 \left(\frac{m_\nu}{m} \right) \quad (10)$$

*) Charged particles, however, would not fit in this category because their electromagnetic interactions would not be weak enough.

This constraint is violated for asymmetric relics ($f \approx 1$) for $M \gtrsim 10 M_N$ as required by accelerator searches. Therefore, asymmetric relics must be short-lived. If annihilation in inhomogeneities has been avoided by symmetric relics ((7b) and (7c)), the constraint (10) requires that long-lived ($\tau > t_0$) relics satisfy

$$\frac{m}{m_N} \lesssim 3 \times 10^3 \quad \text{for} \quad f \approx 10^{-6} \left(\frac{m}{m_N} \right) \quad (11a)$$

$$\frac{m}{m_N} \lesssim 10^{11} \quad \text{for} \quad f \approx 10^{-10} \quad (11b)$$

ii) Chemical versus physical masses. To have avoided catastrophic annihilation during recent epochs, symmetric relics must have been shielded in nuclei, or possibly atoms. It would be expected, then, that such exotic particles would be associated with ordinary terrestrial material. If so, very heavy relics would produce anomalous isotopes. The data¹⁵⁾ on chemical versus physical masses suggest that $\rho \lesssim 10^{-4} \rho_N$. This leads to much more severe constraints than (11) but it must, of course, be assumed that the relics are well mixed with ordinary matter:

$$\frac{m}{m_N} \lesssim 10 \quad \text{for} \quad f \approx 10^{-6} \left(\frac{m}{m_N} \right) \quad (12a)$$

$$\frac{m}{m_N} \lesssim 10^6 \quad \text{for} \quad f \approx 10^{-10} \quad (12b)$$

The first case (12a) is already eliminated by accelerator searches¹³⁾ so that $\tau < t_0$ for $f \approx 10^{-6} (M/M_N)$.

iii) Directed searches for anomalous nuclei. Much lower limits exist on the fractional abundance of anomalous isotopes of specific nuclei¹⁶⁾. Provided the exotic relics participated in primordial nucleosynthesis²⁾, they may be excluded for $M \lesssim 100 M_N$.

iv) Decays of exotic relics. Muons produced in the decay of long-lived relics offer the most sensitive probe of the decays of such particles. This is because the long range of energetic muons permits a large volume of surrounding material to be viewed by a relatively small, compact detector. The Case-Wits-Irvine (CWI) detector¹⁷⁾, for example, was a thin, flat detector of $\sim 174 \text{ m}^2$ area in a vertical plane in a mine about two miles beneath the surface. The muon range is about $1 \text{ m} \times E_\mu \text{ (GeV)}$ and $E_\mu \lesssim M/2$. The observed angular distribution of muons in the CWI detector shows two peaks, one at small zenith angles, due

presumably to surviving atmospheric muons, and one at large angles, presumably produced by charged current interactions of ν_μ in the surrounding rock. To derive a limit on muonic decay modes of massive particles we concentrate on the large angle muons ($\theta > 50^\circ$), where the background due to atmospheric muons is negligible. About 100 events with $\theta > 50^\circ$ were observed in 3.8 years. If we assume no more than $\frac{1}{4}$ of these are due to decays, we obtain

$$\frac{25}{3.8} \text{ year}^{-1} > B_\mu \left(\frac{m(4\text{eV})}{2} \right) \left(\frac{f}{\tau} \right) A_{\text{eff}} (\text{m}^2) \times 1.8 \times 10^{30}$$

where B_μ is the mean number of muons per decay and the density of the rock is taken to be 3 gm/cm^3 . The effective projected area for $\theta > 50^\circ$ is $\sim 33 \text{ m}^2$, so we find

$$\left(\frac{f}{\tau} \right) \left(\frac{m}{m_N} \right) B_\mu \lesssim 2 \times 10^{-31} \text{ year}^{-1} \quad (13)$$

This limit could, of course, be changed somewhat (for example, there are also over 100 events reported with no measurement of the angle) but it is typical of the kind of number that would be obtained from these data.

Another limit may be derived from hadronic (or electromagnetic) decay modes. Here, there is the advantage that the energy of the event can be estimated from the number and extent of shower tracks and/or the energy deposition in the detector. However, the range in rock of these cascades is only about one metre so that the observation volume is much smaller than is the case where muons are observed. On the other hand, the background due to high energy neutrino or muon interactions in this volume is negligible.

Krishnaswamy et al.¹⁸⁾ have reported a total of five or six nearly horizontal or upward-moving large cascades with energies of order several hundred to one thousand GeV, from a total exposure of about 150 m^2 at three depths. Assuming these are due to decays of massive particles leads to the constraint

$$\left(\frac{f}{\tau} \right) B_H \lesssim 2 \times 10^{-32} \text{ year}^{-1} \quad (14)$$

If the reported events are indeed due to the decay of relic heavy particles with $M \sim 10^3 M_N$, the data of Ref. 18) are in conflict with the limit from Ref. 17) unless $B_\mu \lesssim 10^{-2} B_H$. It should be noted that there is no conflict between the raw data of the two experiments since energy is not estimated in the CWI experiment.

v) Annihilation radiation. For symmetric relics not shielded from annihilation during the condensation of galaxies, solar systems, readers, etc., some limits can still be obtained from observations of the gamma-ray background. The hadronic and electromagnetic cascades following annihilation would result in the production of,

among other things, high-energy gamma-rays. Observations of the gamma ray background¹⁹⁾ reveal that it drops sharply above ~ 10 MeV; the isotropic flux above 100 MeV is $\approx 10^{-5} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$. Since we are concerned with $M \geq 10 M_N$ and since annihilation would have occurred for red shifts $Z \lesssim 10$, this flux provides a conservative limit on the abundance of annihilating relics:

$$f B_\gamma \lesssim \frac{1}{n_N} \left(\frac{4\pi}{c} F_\gamma \right) \lesssim 10^{-7} \quad (15)$$

In (15), B_γ is the number of gammas per annihilation; for the nucleon density we have assumed $n_N \approx 10^{-10}$, $n_\gamma \approx 4 \times 10^{-8} \text{ cm}^{-3}$.

For $M \geq 10 M_N$, $B_\gamma \geq 3-10$ (Ref. 20) so that annihilating symmetric relics would have produced too much radiation unless $f \lesssim 10^{-8}$. This constraint is consistent with (7c) but excludes (7b). Symmetric relics with $f \geq 10^{-8}$ must have been shielded from annihilation; they would, therefore, be expected in ordinary terrestrial material.

In summary, then, a combination of terrestrial observations combine to exclude new, long-lived ($\tau > t_0$) exotic particles unless their primordial abundance is very small ($f \ll 10^{-5}$). Direct detection of "light" ($M \lesssim 100 M_N$) relics should be possible¹⁶⁾ at very low abundance levels ($f \geq 10^{-16}$). If symmetric relics avoided combining with ordinary matter, they would have been vulnerable to annihilation during recent epochs. Those with $f \geq 10^{-8}$ may be excluded by comparison with the observed gamma-ray background¹⁹⁾. Provided they are not "too" stable, even long-lived very low-abundance relics could (iv) reveal their presence through their occasional decays.

5. CONSTRAINTS ON SHORT-LIVED RELICS

With the exception of relics with very low abundance, new long-lived hadrons may be excluded on the basis of the data outlined above. Short-lived relics do not present themselves for inspection today, but clues to their previous existence may persist. The energy released in the decay of exotic new particles provides a probe for short-lived relics.

The physical state of the early Universe is constrained by the abundances of the light elements, mainly deuterium and helium, produced in primordial nucleosynthesis. Although there is little to constrain the earlier evolution, nucleosynthesis offers a probe of the total density (through the early expansion rate: $t^{-1} \propto \rho^{1/2}$) and of the nucleon-to-photon ratio when $t \gtrsim 1$ sec ($T \lesssim 1$ MeV)²¹⁾. Correspondingly, we will offer no constraints on very short-lived new particles ($\tau \lesssim 1$ sec) but will attempt to limit the properties (f, M) of those with $1 \text{ sec} \lesssim \tau \lesssim t_0$.

Before proceeding, we offer an order of magnitude survey of the age of the Universe during various epochs. The present expansion is described by the Hubble parameter H_0 . To allow for the uncertainty in H_0 , introduce a scale h_0 where

$$H_0 = 100 h_0 \text{ km sec}^{-1} \text{ Mpc}^{-1}, \text{ i.e. } H_0^{-1} = 10 h_0^{-1} \times 10^9 \text{ years} \quad (16)$$

and present estimates suggest $0.4 \lesssim h_0 \lesssim 1$. (The present values of any quantity will always be indicated by a subscript zero.) The parameter H_0 defines a critical density separating those models which will expand forever ($\rho_0 \leq \rho_c$) from those which will ultimately collapse:

$$\rho_c = \frac{3H_0^2}{8\pi G} \approx 2 \times 10^{-29} h_0^2 \text{ gm cm}^{-3} \quad (17)$$

It is convenient to write the present density as a fraction of ρ_c : $\rho_0 = \Omega_0 \rho_c$. In terms of Ω_0 and h_0 , the present age of the Universe, for $\Omega_0 \lesssim 1$, is

$$t_0 \approx \left(\left(\frac{1+\Omega_0}{2} \right) h_0 \right)^{-1} \times 10^{10} \text{ years} \quad (18)$$

In the recent past, for sufficiently small red shifts $(1+Z) \lesssim \Omega_0^{-1}$ the age t was

$$t \approx \frac{t_0}{1+Z} \quad (19)$$

For larger red shifts, the age and the density are related by

$$8\pi G \rho t^2 = 1 \quad (20)$$

which leads to

$$\frac{t(\text{years})}{10^{10}} \approx \frac{2}{3} \times \frac{1}{(\Omega_0 h_0^2)^{1/2}} \times \frac{1}{(1+Z)^{3/2}} \quad (21)$$

The Universe at present and during recent epochs is "matter dominated" ($\rho_N \gg \rho_Y$). However, the photon density increases more rapidly than the matter density as we go into the past: $\rho_Y \propto (1+Z)^4$, $\rho_N \propto (1+Z)^3$. Going back early enough, there is an epoch, whose red shift is Z_{eq} , when the matter and radiation densities are equal:

$$1 + Z_{eq} \approx \left(\frac{\rho_N}{\rho_\gamma} \right) \quad (22)$$

Earlier, the Universe is "radiation dominated" and expands according to

$$\frac{32\pi}{3} G \rho t^2 = 1 \quad (23)$$

During these radiation dominated epochs, $t \propto T^{-2} \propto (1 + Z)^{-2}$; for $T \approx 1$ MeV, $t \approx 1$ sec and $Z = Z_{Nuc}$.

Were ρ_N , ρ_γ , H_0 well determined, there would be little uncertainty in estimating the ages of interest to us. In reality, the uncertainties are large. For our numerical estimates we make the following choices

$$Z \approx 10^2 - 10^3, \quad t \approx 10^7 \text{ years} \quad (24a)$$

$$Z \approx Z_{eq}, \quad t \approx 10^6 \text{ years} \quad (24b)$$

$$Z \approx Z_{Nuc}, \quad t \approx 10^{-8} \text{ years} \quad (24c)$$

Relics decaying in the recent past ($Z \lesssim 10^2 - 10^3$) will have produced high-energy gamma-rays. New particles with intermediate lifetimes ($10^7 \text{ yr} \lesssim \tau \lesssim t_0$) are thus limited by the observed gamma-ray background¹⁷⁾. The constraint here is similar to that obtained earlier on the annihilation of symmetric relics (c.f. Eq. (15)); relics more abundant than $f \approx 10^{-8}$ are excluded.

There are a variety of cosmological constraints limiting the properties of more shorter-lived particles²¹⁾. The energy released by their decay may distort the microwave spectrum or contribute too much to the entropy of the Universe. If, for example, when the relics decay, they dominate the photons ($\rho > \rho_\gamma$), too many "extra" photons (relative to nucleons) will have been created. Although more confining limits are possible²²⁾, we shall limit ourselves here to the consequences of this constraint: for $t \approx \tau$, $\rho < \rho_\gamma$. Since the ratio of exotics to photons may be written as

$$\frac{\rho}{\rho_\gamma} = \left(\frac{\rho}{\rho_N} \right) \left(\frac{\rho_N}{\rho_\gamma} \right) = f \left(\frac{m}{m_N} \right) \frac{(1 + Z_{eq})}{(1 + Z)} \quad (25)$$

this constraint requires $\tau < t(Z_*) \equiv t_*$, where

$$1 + Z_* = f \left(\frac{m}{m_N} \right) (1 + Z_{eq}) \quad (26)$$

During the radiation dominated era ($Z > Z_{eq}$) this corresponds to

$$t_* \approx \left(\frac{Z_{eq}}{Z_*} \right)^2 t_{eq} \approx \left[f \left(\frac{m}{m_N} \right) \right]^{-2} \times 10^6 \text{ years} \quad (27)$$

To satisfy the constraints from the gamma-ray observations and primordial nucleosynthesis requires, for $f \geq 10^{-8}$, $\tau \leq \text{Min}(10^7 \text{ yr}, t_*)$. Since there is no constraint for very rapid decays, one is also permitted $\tau \leq \text{Max}(10^{-8} \text{ yr}, t_*)$. Except for very massive particles, very low-abundance relics ($f \approx 10^{-10}$) may avoid these constraints.

6. ILLUSTRATIVE EXAMPLES

We have outlined a series of very general constraints limiting the properties of new, heavy ($M \gtrsim 10 M_N$), relatively stable ($\tau \gtrsim 1 \text{ sec}$) particles. To illustrate the application of these constraints we consider the specific examples listed in Eq. (7) for first-order decays (Eq. (8)) and second-order decays (Eq. (9)). Our results are summarized in Figs 2-4 in which are shown the allowed and forbidden regions of the M_B vs M plane.

For all cases, accelerator searches¹⁰⁾ (for relatively strongly interacting particles) restrict us to $M \gtrsim 10 M_N$. For long-lived relics, searches for anomalous isotopes¹⁶⁾ extend (or are capable of extending) this limit to $M \gtrsim 100 M_N$. We have restricted the range of values for the mass of the mediating boson to $M_B \leq 10^4 M_X$. Higher masses would be comparable to or exceed the Planck mass: we are ignorant of what happens at or beyond this scale, but are generally prejudiced to believe that all global quantum numbers are violated at this scale (no heavy hair).

(A) Asymmetric Relics, $f \approx 1$. If long-lived, such abundant relics would contribute too much mass cosmologically and, if associated with ordinary matter, would have revealed their presence terrestrially through enormously anomalous isotopes. Abundant, asymmetric relics must, therefore, be short lived. The critical epoch t_* after which their density becomes greater than ρ_γ is

$$t_* \approx \left(\frac{m_N}{m} \right)^2 t_{eq} \approx 10^6 \left(\frac{m_N}{m} \right)^2 \text{ years} \quad (28)$$

For masses in the range $(10 - 10^7) M_N$, t_* varies from $10^{-2} t_{eq}$ to $10^{-8} \text{ yr} \approx t_{Nuc}$. The allowed regions shown in Figs 2a and 2b, are restricted to

$$\tau < t_* \quad \text{for} \quad 10 \lesssim m/m_N \lesssim 10^7 \quad (29a)$$

$$\tau < t_{Nuc} \quad \text{for} \quad m/m_N \gtrsim 10^7 \quad (29b)$$

(B) Symmetric Relics, $f \approx 10^{-6} (M/M_N)$. Such relics are really quite abundant. For example, for $M \geq 10 M_N$, the abundance by mass of such relics exceeds 10^{-4} . If long-lived, these new particles would have revealed their presence through anomalous isotopes. If, however, such relics avoided association with ordinary matter, terrestrial experiments would place no constraint. At the same time, though, these symmetric relics would not have been shielded from annihilation during recent epochs. Unless these relics avoided gravitational clustering (e.g.: heavy neutrinos), their annihilation would have produced too many background gamma rays. For this case too, then, new particles must be short-lived. The allowed regions shown in Figs 3a and 3b are restricted to

$$\tau < 10^7 \text{ years} \quad \text{for} \quad 10 \lesssim m/m_N \lesssim 10^3 \quad (30a)$$

$$\tau < t_* \quad \text{for} \quad 10^3 \lesssim m/m_N \lesssim 10^{6.5} \quad (30b)$$

$$\tau < t_{Nuc} \quad \text{for} \quad m/m_N \gtrsim 10^{6.5} \quad (30c)$$

In this case the critical epoch is

$$t_* \approx 10^{-12} \left(\frac{m_N}{m} \right)^4 t_{eq} \approx 10^{18} \left(\frac{m_N}{m} \right)^4 \text{ years} \quad (31)$$

(C) Symmetric Relics, $f \approx 10^{-10}$. Much weaker constraints apply to very low-abundance relics such as, for example, the heavy hadrons discussed by Dover et al.²⁾. The searches for anomalous isotopes¹⁶⁾ would (or, could) exclude long-lived relics with $M \leq 100 M_N$. Except for $M \geq 10^6 M_N$, so that $\rho \geq 10^{-4} \rho_N$, heavier relics of such low abundance might be difficult to detect. Such symmetric relics may even have annihilated in the recent past without producing an excess of gamma radiation. If, however, such relics exist and are incorporated in ordinary matter, they might signal their presence by an occasional decay. Making their decay rate consistent with current limits¹⁵⁾ requires (cf., Eq. (13)), that

$$\tau \gtrsim 10^{21} \left(\frac{m}{m_N} \right) B_\mu \approx 10^{21} \left(\frac{m}{m_N} \right) \text{ years} \quad (32)$$

This constraint is shown in Figs 4a and 4b, where $t_\mu \equiv 10^{21} (M/M_N)$ yr.

Few clues exist, as well, for short-lived relics of such low abundance. Unless a large number of gamma rays ($\gtrsim 10^2 - 10^3$) result from a typical decay, decays in the recent past ($\tau \gtrsim 10^7$ yr) will go undetected. We note that when limits or observations on the background gamma-ray flux at very high energies ($\gg 100$ MeV) become available, significant constraints may be placed on the lifetime of even such low-abundance relics.

For low-abundance relics, the critical epoch is

$$t_* \approx 10^{20} \left(\frac{m_N}{m} \right)^2 t_{eq} \approx 10^{26} \left(\frac{m_N}{m} \right)^2 \text{ years} \quad (33)$$

Only for $M \gtrsim 10^{9.5} M_N$, therefore, is $t_* < 10^7$ yr. For second-order decays $\tau \leq t_0$ is then allowed; this limit is shown in Fig. 4a. For fourth-order decays, $\tau \leq t_0$ is permitted for $M \leq 10^{9.5} M_N$. For $M \gtrsim 10^{10} M_N$, $t_* \leq t_{eq} \approx 10^6$ yr and the restriction is $\tau < t_*$; these limits are shown in Fig. 4b.

We close this section by making some connection with some popular types of exotic particles. Consider, for example, technicolour particles which might have masses $\approx 10^3$ GeV. In (almost?) all favoured technicolour¹¹⁾ models (but not¹¹⁾ all the possible ones) the bosons B responsible for the decays of technihadrons are sufficiently low to be consistent with all the cosmological constraints: $(M_B/M_X) \lesssim 10^{-8}$. One might have been tempted to explore technicolour models with $M_B \approx M_X$ so as to have an apparently grander unification. However, the figures show that this is only allowed if the technihadrons are strongly annihilating and decay through a fourth-order diagram -- see Fig. 4b. A final remark concerns the circumstances under which one might expect exotic particles to be produced asymmetrically (cf., Eq. (7a)) rather than symmetrically. Detailed calculations¹⁰⁾ suggest that it would be difficult to produce particles asymmetrically through reactions involving virtual particles much lighter than the X bosons of grand unified theories. It seems quite likely that in a specific model the bosons responsible for generating the exotics might be the same as the B bosons responsible for their decays. In this case, Fig. 2 would only be relevant for $\log (M_B/M_X) \geq 0$, while Figs 3 and 4 would only be relevant for $\log (M_B/M_X) \leq 0$. These conclusions do not rule out any recently proposed, interesting exotic model that we know of, but they do indicate that cosmology provides non-trivial constraints on the imagination of exotic theorists.

7. SUMMARY AND CONCLUSIONS

It is becoming increasingly clear that, as a probe of the frontier of particle physics, accelerator data must be supplemented by information from terrestrial and astrophysical observations. Such observations can lead to significant constraints on models of particle physics containing new, exotic particles. This approach has already proved valuable in constraining the properties of weakly interacting particles^{2),6),21),23)}. Dover et al.²⁾ and Frampton and Glashow⁴⁾ have extended this analysis to constrain the properties of new hadrons. In view of the increasingly important role of this approach to particle physics, we have attempted a general summary of the constraints on possible new particles from a combination of astrophysical and terrestrial observations.

Our central assumption has been that the standard picture of the early evolution of the Universe¹⁾ is correct so that new, exotic particles would have been produced cosmologically during early epochs. During the subsequent expansion, some relics survive to influence the evolution of the Universe; long-lived relics would be present today. If processes similar to those which have led to the observed baryon asymmetry of the Universe^{8),9)}, operated for these new particles, asymmetric relics of very large abundance ($f \approx 1$) may be expected. Such abundant relics must be very short-lived (Fig. 2). The surviving abundance of symmetric relics may be much smaller. Unless, however, these new particles had much stronger interactions than the usual strong interactions, it is expected¹⁾ that $10^{-10} \lesssim f \lesssim 1$. Constraints on intermediate abundance relics ($f \gtrsim 10^{-8}$) require that they too be short lived (c.f. Fig. 3). Fewer constraints exist for very-low-abundance relics and long-lived particles ($\tau \gtrsim t_0$) are possible. If, however, such long-lived particles are unstable, their lifetimes cannot be too short (cf., Eq. (13)). The proposed experiments which will search for proton decay²⁴⁾ may, as a bonus, find evidence for new, exotic relics.

In the absence of a specific model, we find it unlikely that the relic abundance of new particles could be excessively low ($f \ll 10^{-10}$). However, as Frampton and Glashow⁴⁾ have noted, there would be constraints on the lifetime of such particles.

We have illustrated our general outline with several specific examples. We are, however, aware that no new model is likely to fall precisely into any of the categories established here so we have tried to maintain a general approach. Finally, we wish to urge our experimental colleagues to extend observations of the sort outlined here. We cannot over-emphasize the importance to basic particle physics of, for example, extending the limits on anomalous isotopes to higher masses and of limiting the isotropic gamma-ray background at higher energies.

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- We are in addition aware of two functioning experiments, one in the United States by a group from the University of Pennsylvania, and one in the Kolar gold mine by an Indo-Japanese group. Experiments are also being considered in the Soviet Union, France, and West Germany, and by the CERN-Dortmund-Heidelberg-Saclay collaboration.

Figure captions

- Fig. 1 : Examples of possible decays of exotic heavy relics by (a) second-order, and (b) fourth-order diagrams.
- Fig. 2 : Cosmological constraints on the masses of exotic heavy relics and on the virtual particles B responsible for their decays. The case of an exotic asymmetry comparable with the baryon asymmetry as in Eq. (7a), and (a) second-order decays, (b) fourth-order decays.
- Fig. 3 : As for Fig. 2, but for the case of initially symmetric particles which annihilate weakly as in Eq. (7b).
- Fig. 4 : As for Fig. 2, but for the case of initially symmetric particles which annihilate strongly as in Eq. (7c).

(a)

(b)

Fig. I

Fig. 2a

Fig. 2b

Fig. 3a

Fig. 3b

Fig. 4a

Fig. 4b