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NEUTRINO MASSES, LEPTON NUMBER VIOLATION AND UNIFICATION

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ABSTRACT

Lepton number violationg forces occur quite generally in unification schemes of strong and electroweak interactions, with the consequent generation of neutrino masses of the Majorana type. I give a discussion of the subject, trying to keep the arguments at a general level rather than going into model dependent details.

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1. INTRODUCTION

Among the energy scales of elementary particle physics, the following quantities are compatible with being zero: the graviton, the gluon and photon masses, the electron's decay width Γ_e, the proton's decay width Γ_p, and, finally, the neutrino masses m_ν. Whereas we have a dynamical understanding of the vanishing of the first four in terms of suitable gauge principles, $\Gamma_e = 0$ being guaranteed by electric charge conservation, the same is apparently not true for the vanishing (or the smallness) of Γ_p and m_ν. In fact, the supposedly conserved relevant quantities, baryon and lepton numbers, could not possibly correspond to unbroken local symmetries*. For a believer in the currently fashionable Gauge Symmetry Dogma, i.e., that exact symmetries in Nature are local ones, this is enough to want Γ_p and m_ν to be different from zero. Now, of course, the very important recent work on baryon creation in the Universe gives also, for the first time, a good "experimental" reason for the proton to decay. It seems therefore worth while to give a discussion of the possible generation of neutrino masses. This is what I shall do in this talk, trying to keep the various arguments on general grounds, rather than going into model dependent details.

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*) It has been known for a long time[1] that a massless boson coupled to a baryon or a lepton number would introduce discrepancies in the Eötvös experiment unless it had an ultraweak coupling.

It is well known that the standard SU(2) × U(1) theory with the "minimal" Higgs structure, a scalar SU(2)-doublet, describes a strictly massless neutrino. The omission of the right-handed neutrino prevents a Dirac mass term $\bar{\nu}_R\nu_L$, whereas the Majorana mass term $\nu_L\nu_L$ is forbidden by exact lepton number (L) conservation.

However, L is not gauged and, as such, not sacred. Leaving aside the uninteresting possibility of breaking L and getting a zeroth order Majorana mass from the vacuum expected value of a scalar SU(2)-triplet -- which would also explicitly break the $I = \frac{1}{2}$ rule for the strength of neutral currents -- one may think quite generally of some new physics emerging at a mass M greater or much greater than M_W, and containing an inherent L violation. Approximate SU(2) × U(1) invariance at this large mass scale M, together with dimensional counting, leads to the following dominant effective L-violating interaction

$$\frac{f}{M}\,\psi\phi^2\psi\ , \tag{1}$$

where f is a dimensionless coupling, $\psi = (\nu_L, e_L)$ and ϕ is the "minimal" Higgs doublet*. This interaction would produce a Majorana neutrino mass through the vacuum expected value of ϕ

$$m_\nu \simeq \frac{b}{\alpha M}\,M_W^2\ . \tag{2}$$

Depending on the explicit model, f can vary over a wide range of values: from a Yukawa coupling squared $f \simeq \lambda^2$ to the gauge coupling squared $f \simeq \alpha$. Taking for λ the average value $\lambda^2 \simeq 10^{-4}\,\alpha$ one gets

$$m_\nu \simeq (10^{-2} - 10^{+2})\,\frac{M_W}{M}\ \text{GeV}\ .$$

Turned round the other way, the cosmological limit of a few eV for m_ν requires M to be postponed to 10^9 - 10^{13} GeV. On the other hand, if M is as high as the Planck mass, one may still have a neutrino mass of order 10^{-5} eV, which is not without consequences for solar neutrino physics.

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*) The omitted SU(2) indices are meant to be saturated to give a scalar quantity. A possible family structure is also not explicitly indicated.

2. L-VIOLATION IN GRAND UNIFIED THEORIES

The central question then becomes: Do we have any good reason for expecting this L-violating physics to come in at some superhigh energy? How can we be more explicit about neutrino masses and, vice versa what would a neutrino mass signal teach us about the underlying physics?

Herein lies the connection with grand unified theories. In this theoretical framework, there is a basic distinction between theories where a C- and a P-operator can be defined, e.g., the schemes based on SO(10) or E_6, and theories where P-violation is intrinsic, like the smallest scheme based on SU(5). In the first case the right-handed neutrino ν_R participates in the gauge interactions and B-L (baryon minus lepton number), which takes the place of L in the following discussion, is a gauged charge[3],

$$B - L = 2(Q - T_{3L} - T_{3R})$$

which has to be broken. On the other hand, in the case of SU(5) with its reducible representation for fermions, $\underline{5} + \underline{10}$, ν_R is absent and (B-L) is allowed to obey an exact global conservation law, through a mechanism which is interesting in itself[4]. B-L can be written as a linear combination

$$B - L = X + \frac{4}{5}(Q - T_{3L})$$

of a gauged charge plus an ungauged quantum number X, that is -3/5 for $\underline{5}$ and 1/5 for $\underline{10}$, thus commuting with SU(5). Then the spontaneous violation of both X and $(Q-T_{3L})$ with the linear combination B-L exactly conserved gets rid of the Goldstone boson associated with X-violation, since it is "eaten" by the gauge boson carrying $(Q-T_{3L})$. True enough, this picture is tied to the "minimal" Higgs structure for SU(5), but we consider very ugly the possible complication of the Higgs sector, e.g. through a $\underline{10}$ or $\underline{15}$ of scalars, which leads to an explicit violation of X in the Lagrangian, and *a fortiori* of B-L *. Therefore, within the SU(5) model, very much like in the low-energy SU(2) × U(1) theory, one is led to exclude a neutrino mass, either of Dirac or of Majorana type, or at least to postpone it to some post-SU(5) interaction, e.g., gravity, with only a very tiny effect expected, may be of order $m_\nu \sim 10^{-4} - 10^{-5}$ eV [6].

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*) A number of papers exist on this subject, probably initiated by S. Glashow[5].

In the alternative scenario, provided by basically left-right symmetric theories, on the one hand a Dirac neutrino mass is expected, since ν_R is present, and on the other Majorana masses for ν_L and ν_R, since B-L is violated*. Here a clue to understanding the smallness of the observed left-handed neutrino mass is offered by the different transformation properties under weak SU(2) of the various mass terms: $\nu_R\nu_R$ is a singlet, $\bar{\nu}_R\nu_L$ transforms as a doublet, whereas $\nu_L\nu_L$ transforms as a triplet. One is then led to associate the right-handed neutrino Majorana mass, M, with the huge mass characteristic of the breaking of the unifying group down to $SU(3) \times SU(2) \times U(1)$, and the Dirac neutrino mass with a generic quark mass, m, perhaps with its typical generational structure. Barring for the moment a direct $\nu_L\nu_L$ mass term, the observed left-handed neutrino would then acquire, through the diagonalization of the appropriate 2 × 2 matrix, an effective Majorana mass of roughly m^2/M [8]. This is, of course, a special case of Eq. (2), ($m = \lambda\langle\phi_2\rangle = (\lambda/e)\, M_W$), but now we have physical reasons for it.

Several comments are in order here. The first point concerns the size of a possible direct $\nu_L\nu_L$ mass term which could come from the vacuum expected value of a Higgs ϕ_3 which is a triplet under SU(2). This question is tied to the "gauge hierarchy" problem, which requires a "miniaturization" with respect to M of the mass for the Higgs SU(2) doublet ϕ_2 needed to break SU(2) and to give masses to quarks and leptons. The relevant SU(2) invariant effective potential for ϕ_3, after the first breaking at M has taken place, will look like

$$V = \mu^2\phi_3^2 + \lambda\phi_3\phi_2^2$$

with μ and λ both of order M, if no other unnatural "miniaturization" occurs. But then the minimization of V implies a vacuum expected value for ϕ_3 of order $\langle\phi_2\rangle^2/M$, giving in turn a direct Majorana mass to ν_L of the same order of the induced term already discussed.

A second comment concerns the possibility that no Higgs field couples to $\nu_R\nu_R$, so that the right-handed neutrino Majorana mass cannot come from a direct vacuum expected value. A general rule is, however, that it is in any case hard to prevent a huge mass being

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*) The possibility[7] of having (B-L) violated locally but conserved globally, which would still forbid Majorana masses, seems unnatural.

induced by radiative corrections with the previous picture substantially unchanged*. In fact, in models with a large fermionic representation, like E_6, the right-handed neutrino is likely to be only one member of a numerous family of superheavy fermions[10].

A final comment concerns (B-L)-violation, which could also show up in proton decay. A general argument[11] based on dimensional counting and SU(3) × SU(2) × U(1) invariance at the superheavy scale M, very similar to the one that has led to Eq. (1), gives however

$$\frac{\Delta(B-L) \neq 0}{\Delta(B-L) = 0} \simeq \frac{M_W}{M}$$

for the ratio of amplitudes of (B-L)-violating versus (B-L)-conserving processes. As a consequence, e.g., $p \to e^+\pi^0$ is allowed, but $p \to e^-\pi^+\pi^+$ is not. In the simplest picture, with two basic scales only, M_W and M, the (B-L)-violating forces at M could show up through a neutrino mass signal but not in proton decays. The detection of modes like $p \to e^-\pi^+\pi^+$ would indicate the presence of an intermediate scale between M_W and M, which invalidates the dimensional arguments. In constructing models of this kind, with a medium-heavy mass, an eye has to be kept however to the B-$\bar{B}$ asymmetry in the Universe, which could get washed out.

3. CONCLUSIONS

Theories with parity as a short-distance symmetry lead rather naturally to a small but non-vanishing ν_L mass. A reference formula for the size of the effect is $m_\nu \simeq m^2/M$ with M a huge Majorana mass of the ν_R field, associated with the breaking of the group down to SU(3) × SU(2) × U(1) and m a typical quark mass, most likely that of charge 2/3. This is because of the Pati-Salam SU(4) [12] which relates neutrinos with charge 2/3 quarks, and is contained in the prototypes of these theories, SO(10) or E_6. Ten GeV for m requires $M \simeq 10^{11}$ GeV in order to saturate the cosmological bound (m_ν of a few eV). This value is not too far from the currently preferred mass $\simeq 10^{14}$ GeV of the superheavy gauge bosons. Fermions have a tendency to be substantially lighter than the corresponding vectors; this would be especially true for the Majorana mass M if it is generated by radiative corrections[9].

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*) An example of such a theory, based on SO(10), has been proposed by E. Witten[9].

In view of these concepts, the search for neutrino oscillations appears to be of overwhelming importance. A combined effort in all different kinds of possible experiments (reactors, accelerators, deep mines, and solar neutrino observations) may indeed lead to a positive result since the range of values indicated, $m_\nu \sim 10^{-5}$-1 eV, overlaps considerably with the expected sensitivities. Even a particularly low value $m_\nu \simeq 10^{-4}$-10^{-5} eV could, perhaps, be detected by the observation of a time dependence in the solar neutrino flux[6].

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Archives

THE VERY LARGE AND THE VERY SMALL

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INTRODUCTION

The physical world about us has many aspects which are governed by different members of the set of four fundamental forces: gravitation, electromagnetism, the weak interactions and the strong nuclear forces. It is often unnecessary to have a very deep understanding of these forces if one is content to describe everyday phenomena in the relatively peaceful and quiet part of the Universe close to us. Thus the motions of falling apples, stars, galaxies and even the Universe in the large can be understood without knowing how to quantize gravity. Chemical and solid-state phenomena can be adequately described by quantum electrodynamics with values of the fine structure constant and particle masses put in by hand - one does not need to know why they take the values they do. Similarly the gross features of the Sun's output of energy and its lifetime can be understood in terms of a few God-given parameters of the weak and strong nuclear interactions1). We do not need to know the origin of these parameters, though stellar evolution would have been grotesquely different and human life totally impossible if some of them had taken even slightly different values.

We have seen in previous lectures that in recent years great strides have been made in the understanding of the fundamental interactions and in their unification into a simpler and more complete framework2). Among the insights gained from such unified theories is increased understanding of the values of some of the previously arbitrary fundamental constants. For example the grand unification of strong, weak and electromagnetic interactions entails that the fine structure constant be small3). These insights establish an indirect connection between modern theories of matter and everyday phenomena in the Universe about us. If we are to look for more direct manifestations of our new unified theories we must look farther afield than our own peaceful little coner of a non-descript galaxy. The purpose of this lecture is to describe how the behaviour of the Universe on a large scale in time and space is connected with deep aspects of the fundamental interactions which are not directly discernible in our everyday world. Indeed we now see ever more clearly that modern ideas in particle physics exist in intimate symbiosis with some fundamental aspects of cosmology and astrophysics4), such as the origin of matter and the very early history of the Universe.

It is not difficult to understand why the Universe is an ideal arena for studying high energy fundamental physics. One reason is quite simply its large size which provides us with a long lever arm for performing delicate balance experiments or, if you prefer, a gargantuan telescope for magnifying the very small effects of individual particles. For example, the Universe being large contains many neutrinos which it can "weigh" much more precisely than laboratory experiments working with individual neutrinos. A second reason why the Universe is a good high energy physics laboratory is that very violent and energetic events occur "out there" whose conditions are very difficult or impossible to reproduce artificially on our own tranquil planet. For example, while the highest energies presently attainable with our particle accelerators are less than 10^3 GeV, it is believed that particle energies of 10^{19} GeV may be reached in black hole explosions, and were probably routine at very early stages in the Big Bang.

In order to show you how we can utilize these potentialities of the Universe as a high energy physics laboratory, it will first of all be necessary to recapitulate some basic features of the "standard" cosmological model5) starting off from the Big Bang. This model is motivated by the over-all expansion of the Universe today, by the observation of the relic 3^0K microwave radiation, and by the qualitative success of calculations of the primordial abundance of Helium. The success of these nucleosynthesis calculations and the continuing expansion of the Universe impose limits on the number and masses of neutrinos which are much more restrictive than those found in laboratory experiments. Additional information on the nature of the neutrinos may come from experiments searching for the flux of neutrinos emanating from nuclear reactions in the Sun. However, the most exciting interface between cosmology and high energy physics may go back much earlier in time, to an epoch when the Universe was very compressed and typical particle energies were of order 10^{15} GeV. It now seems likely that the origin of all the matter in the Universe may be found in the grand unification of strong, weak and electromagnetic particle interactions at these exceedingly high energies. These grand unified theories also provide a melancholic vision of the ultimate future death of matter in the Universe.

THE STANDARD COSMOLOGICAL MODEL

Observational cosmologists are agreed that the Universe is expanding with the galaxies flying apart from one another. While they may disagree on the rate of expansion, they believe that it is the relic of a primordial explosion - the Big Bang - which took place (10 to 20) × 10^9 years ago. The gross features of the evolutionary history of the Universe in this standard cosmological model are summarized in the Table. Shown are the approximate times at which various important evolutionary milestones are believed to have been passed, the approximate temperature of the Universe at each of these epochs and the corresponding energies of elementary particles.

The best understood epoch in the Table is obviously the present one when the Universe is about 10^{10} years old. Most of the visible matter is now collected in stars which shine by burning lighter elements in order to make heavier ones using reactions like

$$p + p \Rightarrow D + e^+ + \nu_e \quad , \quad p + e^- + p \Rightarrow D + \nu_e \quad ,$$

$$^7Be + e^- \Rightarrow {}^7Li + \nu_e \quad , \quad \text{etc.} \quad , \quad \text{etc.}$$

These reactions emit many electron neutrinos ν_e, are the only known way of creating substantial amounts of elements heavier than Helium, and have generally been considered to be well understood for about 20 years since the work of Bethe, Hoyle and others. Most of the visible stars are collected into galaxies which are in turn gathered into clusters. It is believed$^{6)}$ that our local cluster of galaxies contains no substantial concentrations of antimatter, but only conventional matter. If our cluster contained antimatter as well, then one would expect there to be regions where the matter and antimatter would meet and annihilate, creating high energy photons (γ-rays and X-rays) for which no evidence has ever been seen. Some antiprotons have recently been seen in high energy cosmic rays, but their flux is low enough for them to be explained as the secondary products of collisions involving primary nucleons, not antinucleons. It seems likely that galaxies and galactic clusters may contain invisible "dark" matter in addition to that visible in stars. The existence of this matter is inferred from its indirect gravitational effects, and it could take many forms such as mini-black holes, Jupiter-sized planets, dust clouds, or even neutrinos.

The different galactic clusters are receding from one another at rate of about 30 kilometres per second for each million light-years that they are presently separated. A natural question is whether there is sufficient matter in the Universe for its gravitational attraction to cause the Universe to collapse back on itself eventually. This would require the present matter density to exceed about 2×10^{-29} gm per cubic centimetre, and current belief is that the matter density is about an order of magnitude less than this critical density, in which case we expect the Universe to continue expanding indefinitely far into the future. Near the end of this lecture we will return to this distant future, for the moment let us restrict ourselves to the extrapolation of the present expansion back into the past. This extrapolation is relatively simple and reliable because the Universe appears to be rather homogeneous and isotropic on a large scale. Of course, the speaker and audience are evidence that local inhomogeneities exist, but on a larger scale the distribution of galactic clusters looks similar in all directions from whatever point they are viewed.

A naïve extrapolation backwards in time of this present symmetric expansion suggests that there is a singularity in our past. Matter would have been very compressed close to this putative singularity, and we are familiar with the idea that matter heats up when it is compressed. When heated up sufficiently, the matter would have been in thermal equilibrium with a "bath" of hot radiation. As the Universe expanded and cooled this radiation would first have decoupled from the matter and then have cooled down still further according to the simple formula

$$\frac{T_{\text{now}}}{T_{\text{decoupling}}} \approx \frac{R_{\text{decoupling}}}{R_{\text{now}}}$$

where R is the characteristic size of the Universe at any given time. Calculations indicate that $(R_{\text{decoupling}}/R_{\text{now}})$ should be about 10^{-3}, and that this radiation relic from the Big Bang should now have temperature of a few degrees Kelvin. Lo and behold, just such a background radiation was found in 1964 to 1965 by Penzias and Wilson[7)] with an apparent temperature of about 3^0 K just as expected in the Big Bang model. Subsequent observations have confirmed an apparent black-body spectrum for this radiation, and found that it is isotropic to better than one part in 10^3. Its existence is considered one of the two greatest successful predictions of the Big Bang model.

Because of this black-body radiation, the Universe now contains very many photons, about 300 per cubic centimetre. However, there seem to be relatively few baryons, neutrons and protons, in the Universe as a whole, their density being of order 10^{-6} per cubic centimetre. This means that the ratio of baryons to photons is very small:

$$\frac{N_B}{N_\gamma} \approx 10^{-9\pm1}$$

Before the advent of grand unified theories of particle interactions this number was either puzzled over or ignored. If there is no antimatter in the Universe, why is N_B/N_γ so small and not of order unity? If the primordial "soup" had started off symmetric with equal amounts of matter and antimatter, surely they would have annihilated to form many more photons than the "small" excess of 10^9 or so indicated above? We will return later to the possible resolution of this puzzle: for the meantime let us continue our rearward odyssey into the Charybdis of the Big Bang and encounter its second great success.

The previous milestone in the evolution of the Universe shown in the Table was when the temperature was in excess of 10^{10} ^{0}K, and hence for particle energies to exceed the 1 MeV characteristic of the neutron-proton mass difference and the mass of the electron. When the temperature was somewhat higher than this there would have been essentially equal numbers of neutrons and protons, and the light particles - electrons, positrons, and neutrinos - would all have been in thermal equilibrium. As the temperature T dropped the fraction of neutrons would have dropped below 1/2 because of the Boltzmann suppression factor $\sim e^{-M/T}$ and the fact that $m_n > m_p$, as seen in Fig. 1. Also, as T dropped below 10^{10} ^{0}K the neutrinos would have decoupled from the electrons and positrons because the thermal energies would have been insufficient for the reactions $e^+e^- \to \nu + \bar{\nu}$ to proceed. As the temperature dropped further below 10^9 ^{0}K the thermal energies would have been sufficiently low for any nuclei formed to avoid being disintegrated. In fact, this primordial nucleosynthesis would have been very inefficient for making nuclei with $Z > 4$ because of the famous gap at mass 5. However, Helium would have been produced copiously at this time, and also some Deuterium. Since ^{4}He contains two neutrons and two protons, the Helium mass fraction Y would have been essentially twice the neutron fraction at the time of nucleosynthesis. The neutron fraction at this time is in fact rather sensitive to the precise rate of expansion of the Universe, which is in turn controlled by the density of matter and the number of "light" particles with masses less than 1 MeV such as neutrinos. We will return later to this sensitivity to the number of neutrinos. For the moment we content ourselves by noting that calculations of primordial nucleosynthesis have yielded a Helium mass fraction Y of order 25%, and that this is qualitatively consistent with most present astrophysical data once the subsequent generation of a small amount of helium by first generation stars is subtracted out.

This second great success of the Big Bang model suggests that it is legitimate to extrapolate our present expanding and cooling homogeneous and isotropic Universe back to an epoch when it was 10^{15} times younger and 10^{11} times hotter than it is today. What happened still earlier? We know of no reason why a naïve extrapolation back to yet earlier times should not be valid. On the other hand we have no evidence either that such naïveté is in fact justified. Nevertheless, later in this lecture we will extrapolate back to a time 10^{-38} times shorter, when the temperature was 10^{18} times higher even than at nucleosynthesis. But before indulging in this hubris we will first see what the relatively well-understood epochs of the Big Bang can tell us about particle physics, and about neutrinos in particular.

NEUTRINOS IN PARTICLE PHYSICS

Neutrinos are very light, electrically neutral particles ν which appear to have only weak interactions$^{2)}$. They seem to come in at least three varieties, each one associated with a different charged lepton as indicated here:

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}, \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}, \quad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}, \quad \dots ?$$

Laboratory experiments have established upper limits on their masses which are of varying stringency. From Tritium to $^3\mathrm{He} + e^- + \bar{\nu}_e$ decay we know that $m_{\bar{\nu}_e} < 35$ eV, about 10^{-4} of the electron mass. From $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ decay we know that $m_{\nu_\mu} < 600$ KeV or about 10^{-2} of the muon mass, and from $\tau^- \to (3\pi)^- + \nu_\tau$ decay we know that $m_{\nu_\tau} < 200$ MeV or about one tenth of the tau mass. There is no fundamental reason known why the neutrino masses should be strictly zero, and our present prejudices indeed suggest that they should be non-zero. In other instances, Nature associates the masslessness of a particle with an exact local conservation law or symmetry. For example, the masslessness of the photon is believed to be associated with the local conservation of electric charge. There is no known local charge which could be similarly associated with the masslessness of the neutrinos. Modern grand unified theories of the fundamental interactions go further and suggest that the neutrino masses may in fact be of order 1 eV, give or take a few orders of magnitude.

Another uncertainty about neutrinos concerns the total number of different species. We have direct evidence for two - the ν_e and ν_μ and indirect evidence for the third - the ν_τ. Any other would presumably be associated with leptons heavier than the τ which we have not yet been able to detect in our laboratories. There are very indirect indications from the strength of neutral weak interactions that there cannot be more than about a thousand such very heavy leptons. A more direct limit on the total number of neutrinos comes from the fact that nobody has ever seen a decay of the type $K^\pm \to \pi^\pm$ + nothing. If we interpret the "nothing" as a sum of all possible types of invisible neutrinos with masses less than $(m_K - m_\pi)/2$, then we get an upper limit of about 6000 on the total number of neutrino types! We know of no better limit on the number of neutrinos coming from present-day laboratory experiments on particle physics, though big improvements are possible with new particle accelerators now being planned. However, we will see in a moment that cosmology can already give us much more stringent limits on the number of varieties of neutrinos.

ASTROPHYSICAL AND COSMOLOGICAL RESTRICTIONS ON NEUTRINOS

The first connection between the very large and the very small comes from an aspect of astrophysics that we think we understand very well, namely the Sun. As mentioned earlier the Sun is believed to shine because of nuclear interactions in its interior which emit many electron neutrinos. Experiments have been set up to look for these neutrinos via interactions of the form

$$\nu_e + {}^{37}Cl \to e^- + {}^{37}Ar$$

After some initial doubts, it now seems clear that solar neutrinos are indeed being seen at a rate of (2.2 ± 0.3) Solar Neutrino Units (SNU), where one SNU corresponds to 10^{-36} Argon atoms produced per second per Chlorine atom. The number observed is rather lower than the number expected, which is about 5 to 9 SNU, though the calculations are very difficult to make precise. Various more or less serious mechanisms have been proposed to explain away the possible discrepancy. One somewhat frivolous idea is that perhaps the Sun has stopped shining. Since the electromagnetic radiation that we see takes about 10^6 years to filter up from the interior of the Sun, whereas neutrinos reach us in $8\frac{1}{2}$ minutes, it is logically possible that the nuclear reactions at the core of the Sun have indeed stopped, and that we are living on borrowed time with the extinction of the Sun's light and warmth an imminent catastrophe. A rather more serious possibility is that some major or minor detail of the conventional nuclear physics calculations of the Sun's interior has gone awry. It should be pointed out that the solar neutrino experiments to date have only been sensitive to a small tail in the distribution of neutrino energies expected to come from the Sun, and that this minor aspect may well have been miscalculated without our ideas about the central energy-producing reactions in the Sun being wrong. But suppose the observations and the stellar models are both correct - what could then be the explanation of the solar neutrino puzzle?

One possibility is that after all, the neutrinos do have masses. The states with fixed masses need not be the particular combinations of neutrinos (ν_e, ν_μ and ν_τ) which are observed in laboratory experiments to be produced in association with e, μ or τ respectively. Suppose that the neutrinos ν_e produced in the Sun are actually linear combinations $\alpha_1\nu_1 + \alpha_2\nu_2 + \ldots$ of states ν_i with definite masses. As they propagate through space, states ν_i which are produced with the same energy will propagate with different velocities because of their different masses. This means that our initial neutrino wave $\alpha_1\nu_1 + \alpha_2\nu_2 + \ldots$ will arrive at the Earth as a different linear combination $\beta_1\nu_1 + \beta_2\nu_2 + \ldots$ which will in general correspond to a combination $a_e\nu_e + a_\mu\nu_\mu + a_\tau\nu_\tau + \ldots$ of neutrinos which is not a pure ν_e state. In this case the number of ν_e arriving at the Earth will be reduced by a factor of $|a_e|^2$ compared with that expected, and there will be the same reduction in the number of SNU observed:

$$\frac{\text{SNU seen}}{\text{SNU expected}} = |a_e|^2 < 1$$

For this explanation of the reduced number of SNU observed to be valid, it is necessary that the mass differences between the different states ν_i not be too small, in fact greater than about 10^{-5} eV. This is consistent with the cosmological constraints on neutrino masses to be discussed shortly, as well as with the weaker limits on neutrino masses coming from laboratory experiments. However, it is still not clear that the discrepancy between the observed and expected number of SNU is really serious, and many other explanations are still possible besides that of massive neutrinos.

If neutrinos really do have masses, there is another interesting astrophysical method to "weigh" them by using the large scales afforded by the Universe. The point is that when a supernova collapses and dies, many neutrinos are emitted. Since the different mass states would propagate towards us at different velocities, it is possible that if such a collapse occurred many light-years away, there would be measurable time delays between the arrival times of the pulses of different types of neutrinos. Some of the large underground experiments now being built to look for the decays of protons expected in some grand unified theories of particle interactions may also be able to detect these staggered death-throes of distant supernovae.

In the meantime, some cosmological considerations already give us considerable restrictions on the masses and numbers of neutrinos. They have their origins[4)] in the discussion of nucleosynthesis in the standard Big Bang model. When the temperature was about 10^9 ^{0}K and the neutrinos decoupled, all neutrinos with mass much less than about 1 MeV would have been produced in large numbers essentially independent of their masses. Analogously to the photons which decoupled later and have been observed[7)] experimentally, we must now be bathed in an invisible black-body radiation "sea" of about 10^3 neutrinos per cubic centimetre with a temperature of about 2^0 corresponding to thermal energies of order 10^{-4} eV. All except the very lightest of such neutrinos would now be very non-relativistic. They would therefore contribute to the present matter density of the Universe in proportion to the sum of their masses. At the moment, the Universe does not seem to be on the verge of collapsing under its own gravitational attraction, which gives us an upper limit on its mass density. The present upper limit on the density of the Universe in turn implies an upper limit of about 100 eV on the sum of the masses of all neutrinos much lighter than 1 MeV. Since we already know from laboratory experiments that the electron and muon neutrinos are lighter than 1 MeV, this cosmological limit applies directly to them. Even neutrinos or other heavy leptons with higher masses are also restricted by cosmology, as long as they are stable. We see from Fig. 2 that the mass density of such heavy leptons would cause the Universe to collapse gravitationally if the masses were between about 100 eV and a few GeV. To establish these limits one must believe in the standard Big Bang cosmological model back somewhat before the epoch of nucleosynthesis, but this extrapolation is relatively conservative compared with those we will be making in the next section.

The Big Bang model can also be used to make arguments against heavy stable hadrons as well as neutral leptons In this case, however, we do not use the relatively weak constraint imposed by the present matter density of the Universe. Instead we use the fact that such heavy stable hadrons would form unusual heavy isotopes of common elements such as Oxygen. Stringent upper limits have been placed on the abundances of such heavy isotopes which argue against stable hadrons with masses up to about 40 GeV. For comparison, the best limit to date on stable hadrons produced by high energy particle accelerators only restricts them to masses above about 5 GeV.

We have seen that cosmology establishes limits on the possible masses of elementary particles which are much more restrictive than those established with particle accelerators. Another very dramatic limit from cosmology is on the total number of different neutrino types. Remember that neutrinos with masses much less than 1 MeV are very copious around the time of nucleosynthesis. They make a substantial contribution to the total energy density and pressure due to elementary particles in the early Universe, and thereby affect its expansion rate. The mass fraction of neutrons in this era is sensitive to the rate of expansion of the Universe, and this in turn controls the Helium fraction Y which is just twice the neutron fraction. Numerically, the effect of adding a left-handed neutrino and its associated antineutrino to the primordial "soup" is to increase Y by about 1%. The present value of Y is about 30%, with the contribution of primordial nucleosynthesis estimated to be about 25%. This restricts[4)] the number of different neutrino types to about 3 or 4, as seen in Fig. 3. Compared with the laboratory limit of several thousand types this is a considerable improvement, though it should be remembered that this limit only applies to neutrinos weighing considerably less than 1 MeV.

THE ORIGIN OF MATTER

We saw in the previous section that astrophysics and cosmology can be of great use to particle physics in restricting the possible numbers and masses of elementary particles. In this section we will see how grand unified theories of particle interactions may return the compliment by explaining a long-standing cosmological puzzle, the origin of matter. Previous applications of nuclear physics have shown how the heavy elements observed in Nature can have been created out of the lighter elements in stars. Going further back in the history of the Universe, the creation of the lighter elements, Helium and Deuterium, has been explained by primordial nucleosynthesis in the Big Bang. The remaining problem is the origin of the neutrons and protons used in this synthesis, with the challenge of understanding why we only see[6)] matter and no antimatter in our local cluster of galaxies, and by extrapolation in all the visible Universe.

No-one was ever able to give a satisfactory explanation of these mysteries in terms of the conventional electromagnetic, weak and strong nuclear forces seen and studied at low energies. Thus to seek an explanation we must go on to higher energies corresponding to higher temperatures and hence earlier eras in the expansion of the Universe. It has been argued in previous lectures that at very high energies strongly interacting hadronic particles act as if they are made of almost free constituents called quarks. We therefore analyze the very early hot "soup" that was the Universe in terms of quarks and leptons and the relatively feeble interactions between them. The problem of the present dominance of matter over antimatter then becomes the problem of understanding why the density of quarks in the primordial "soup" should have been greater than the density of antiquarks. Calculations indicate that if this trick could be realized in some way, then essentially all the antiquarks would have combined with quarks when the temperature fell to about 10^{13} ^{0}K corresponding to an energy of 1 GeV, forming mesons comparable in number to the present number of photons. However, if there had been a primordial excess of quarks by about 10^{-9} of the total number of quarks and antiquarks, then a similar fraction of quarks would have been left over after the process of meson formation, rather like the wallflowers at a dance. These wallflower quarks would have grouped together into baryons, protons and neutrons, and would survive today as the observed matter density $N_B \approx 10^{-9}$ of the number of photons N_γ.

So how do we establish a net quark asymmetry of about 10^{-9} ? The explanations proposed in the bad old days included starting the Universe off with only quarks and generating 10^9 times more quark-antiquark pairs by mysterious dissipative phenomena. Another response was simply to abandon the problem by postulating a small primeval quark asymmetry when the Big Bang started. A much more aesthetic initial condition would be to have equal numbers of quarks and antiquarks, and hence zero net baryon number. In order to generate the observed non-zero net quark or baryon density, it is therefore necessary to postulate interactions which change baryon number. Although no such interactions have ever been seen, there is no sacred law preventing their existence, because there exists no massless particle which could be associated with a law of baryon convervation. Indeed, it is commonly believed that baryon number is not conserved in the strong gravitational fields associated with black holes.

As discussed in the previous lecture, interactions changing baryon number are the rule rather than the exception in grand unified theories of particle interactions. The simplest example of such a transition is the annihilation of two quarks to make an antiquark and an antilepton: $q + q \rightarrow \bar{l} + \bar{q}$ which changes the net quark number by -3 and hence reduces baryon number by 1. Such interactions should cause protons and bound neutrons to decay via modes like $p \rightarrow e^+ + \pi^0$ or $n \rightarrow e^+ + \pi^-$. So far laboratory experiments have not revealed such decays, and have instead established a lower bound on the nucleon lifetime of about 10^{30} years. The lifetime expected for these decays is very sensitive to the mass of the heavy vector particle X, cousin of the photon, which is expected to be the carrier $(q + q \rightarrow X \rightarrow \bar{l} + \bar{q})$ of the "hyperweak" baryon number changing interaction. The lower limit on the nucleon lifetime gives a lower bound on the mass of the X particle of order 10^{14} to 10^{15} GeV. This may seem unbelievably high when compared with the masses of other elementary particles, leptons, quarks etc., but it is still much lower than the so-called Planck mass of order 10^{19} GeV at which the quantum effects associated with gravity probably become strong and unmanageable. In fact, when one tries to put the known fundamental interactions into a grand unified theory, one finds very naturally that the unification should occur at or slightly below an energy scale of 10^{15} GeV. The exchanges of particles with masses of this order should cause the proton to decay in 10^{33} years or less, and a number of experiments to look for protons decaying within this lifetime are now being prepared.

In order to exploit these possible baryon number changing interactions in the early Universe, we have to be foolhardy enough to extrapolate the standard cosmological model back to temperatures above 10^{27} ^{0}K, corresponding to particle energies above 10^{14} GeV. It is only in this very early era that one can expect a significant change in the net baryon density of the Universe to have taken place. However, in order for a net baryon asymmetry to have been generated, various properties must be satisfied by the baryon-number-changing interactions. Many of these conditions were enumerated by A.D. Sakharov in a paper8) published in 1967, though his work was long before the presently fashionable grand unified theories came into existence.

The first requirement is that the baryon-number-changing interactions should violate the particle-antiparticle symmetry known as charge conjugation or C. Otherwise, starting from an initial state with equal numbers of quarks and antiquarks they will always generate equal numbers of quarks and antiquarks. Furthermore, the baryon-number-changing forces should not be left unchanged by the combined operation of changing particles into antiparticles and mirror reflexion, known as CP. This transformation would change a particle moving in one direction into an antiparticle moving into the opposite direction. Hence, if it were an exact symmetry the Universe would always contain equal numbers of quarks and of antiquarks if it had started out that way. The third requirement is that the evolution of the early Universe must possess an "arrow" of time". If they did not, a perfectly general symmetry which is believed never violated, namely invariance under the combined operations of particle-antiparticle interchange, mirror reflexion and reversal of the direction of time (CPT), would leave the state of the Universe unchanged and guarantee equal numbers of quarks and antiquarks.

The three properties of C (particle-antiparticle) asymmetry, CP (particle-antiparticle and mirror reflexion) asymmetry and the existence of an "arrow of time" are all believed to be present for grand unified particle interactions in the very early Universe. As discussed in previous lectures, we know that the familiar weak forces are not symmetric under either C or CP, and we have every theoretical reason to expect the same to be true for forces changing quark or baryon number. The required "arrow of time" is provided by the expansion of the Universe. As it expands it cools, and the interactions changing the net quark number become too slow to keep up with the expansion rate, so that they are no longer in thermal equilibrium. Then any quark-antiquark asymmetry that is generated by C- and CP-asymmetric forces cannot be "boiled away" by other baryon-number-changing interactions.

Using these basic physical principles, a number of different models for generating a net baryon asymmetry have been proposed. In the simplest one to visualize, very early in the Universe when the temperature was very hot there would have been many superheavy particles X and their antiparticles $\bar{X}$. The X particles produced could have decayed either into a pair of quarks or into an antiquark and an antilepton. Conversely, their antiparticles $\bar{X}$ could have decayed into pairs of antiquarks or into a quark and a lepton. In the absence of particle-antiparticle symmetry and its combination with mirror symmetry, there is no reason why the fraction of X particles which decayed into pairs of quarks should be the same as the fraction of their antiparticles decaying into pairs of antiquarks. Under these circumstances, starting with equal numbers of particles and antiparticles we can finish up with unequal densities of quarks and antiquarks, as illustrated in Fig. 4.

Such a mechanism for generating a difference between the densities of quarks and antiquarks, and hence an eventual relative factor of 10^{-9} between the densities of baryons and photons today, would be a tremendous advance in our understanding of the nature of the matter of the Universe if its validity could be proved. Unfortunately, believing it requires an enormous extrapolation back into the distant past of the Universe, and our evidence for it can only be very indirect for the foreseeable future. Even the existence of forces which change quarks into antiquarks and hence change the net number of baryons is still just a theoretical speculation. If such forces do exist, then we arrive at a rather melancholic vision of the future of our Universe. If, as seems likely, it does not contain a sufficient density of matter to cause it to collapse back on itself into a new "anti-Big Bang" then the Universe will continue to expand forever. As it continues to expand, all the matter that it contains will gradually decay, perhaps within a time-scale of 10^{33} years. The only particles left will be the completely stable electrons, positrons, neutrinos and photons. Competing with this disintegration will be a tendency for matter to gravitate together into black holes. However, even these black holes will eventually explode in bursts of radiation and particles. So the distant future of our Universe may be a diminishing miasma of disintegrating matter, punctuated by the occasional pyrotechnic black hole explosion.

SYMBIOSIS BETWEEN COSMOLOGY AND PARTICLE PHYSICS

We have seen that there are many deep connections between modern cosmology and astrophysics on the one hand, and current developments in particle physics on the other - the very large and the very small. It is indeed a symbiotic relationship with each physical discipline aiding the other in the pursuit of its goals. Relatively well-understood aspects of cosmology and astrophysics provide the particle physicists with strong restrictions on the numbers and properties of the particles, especially neutrinos, that they are allowed to put into their theories. Conversely, some tried and tested aspects of particle physics - and some much more speculative - give us new ways of pondering some of the most profound cosmological problems such as the origin of matter itself. But the daring of our speculations should not blind us to the incompleteness of our understanding and I recently came across 9) a wise reminder of the modesty of our achievements:

"... whoever opens his eyes and ears and tries to remember what the old people said, might fill the emptiness of his thought by this or that knowledge".

(Apatac, an eskimo of the Noatak River, as recounted by Knud Radmussen in "Die Gabe des Adlers".)

Table

Time	Event	Temperature	Typical Energy
10^{-43} seconds	? - Quantum gravity effects are strong	10^{32} °K	10^{19} GeV
10^{-33} seconds	Quarkosynthesis - The predominance of matter established?	10^{27} °K	10^{14} GeV
100 seconds	Nucleosynthesis - Helium and Deuterium created	10^{9} °K	10^{-4} GeV = 1/10 MeV
10^{6} years	Photon decoupling - The background radiation originates	10^{3} °K	10^{-10} GeV = 1/10 eV
10^{10} years	Galaxies, stars and we exist	$\underbrace{3^0\text{K} \quad . \; 10^{-3} \text{ to } 10^{-4} \text{ eV}}$ for background radiation, but no uniform temperature throughout the Universe	
$10^{31\pm2}$ years	All matter decays ?		

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FIGURE CAPTIONS

Fig. 1 : The mass fractions of neutrons, protons and light nuclei such as Helium 3, Helium 4, Deuterium and Tritium, taken from a calculation of primordial nucleosynthesis. Figure adapted from Ref. 4).

Fig. 2 : Cosmological limits on the masses of stable neutral leptons or "heavy" neutrinos. If there were any such objects with masses between about 100 eV and a few GeV their mass density would be higher than the critical density for continuing expansion, and the Universe would eventually collapse under its own gravitational attraction. Figure adapted from Ref. 4).

Fig. 3 : The sensitivity of the present Helium abundance Y to the number of "light" neutrinos with masses much less than about 1 MeV. The upper limit of 25% on the primordial value of Y suggests that there are at most three or four "light" neutrinos and their antineutrinos. Figure adapted from Ref. 4).

Fig. 4 : A calculation showing how by starting at high temperatures with equal densities of X particles and $\bar{X}$ antiparticles, their decays may ultimately generate an asymmetry between the densities of quarks and antiquarks. Y_+ is the sum of the densities of X and $\bar{X}$ particles, Y_- is their difference. Y_B is the net quark-antiquark asymmetry. Figure adapted from E.W. Kolb and S. Wolfram, Caltech preprint OAP-579 (1980).