Thank you for the invitation.

A POSSIBLE REASON FOR

THE BEH MASS 126 GeV

AND A

COSMOLOGICAL IMPLICATION

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1 INTRODUCTION

In the standard model (SM) of particle theory there exists what has been called "the scandal of the fermion masses" meaning that none of the twelve quark and lepton masses have been satisfactorily explained by theory. On the other hand, the masses of the spin-one bosons, the photon, gluon, $W^{\pm}$ and Z are well understood in terms of symmetry breaking. Now, there is one additional boson, with spin-zero, and the issue is whether its mass can be explained.

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Surely the most dramatic discovery in experimental high-energy physics so far this century is that of the Brout-Englert-Higgs boson (H) which completes the discovery of all the particles in the minimal standard model. Equally dramatic is the non-discovery of any other particle in the mass range which has so far been investigated. Given what we now know, it is very reasonable to assume there are no other particles at low energies, and that all that exists is the $SU(3)_C \times SU(2)_L \times U(1)_Y$ standard model with three quark-lepton families and only one scalar whose mass is measured as $M_H \simeq 126$ GeV.

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At large scales, classical gravity is well described by general relativity and we assume that this is the theory which governs the behavior of the universe as a whole. Although large black holes are known to exist, we will ignore the effects of possible virtual black holes in microscopic processes because there is no fully satisfactory theory of quantum gravity at small scales.

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In the present note, we shall offer a speculation which provides a possible reason for $M_H \simeq 126$ GeV, as well as saying something about the fate of dark energy in the extreme future of the Universe.

In gauge field theory, an important formal development was the discovery of the instanton solution . For example, this was once proposed as the key to understanding the QCD of strong interactions. In this note, the instantons of electroweak interactions will play a central role.

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2 BUBBLE NUCLEATION

The effective potential $V(H)$ of the standard model possesses a local minimum where $< H > \simeq 248$ GeV at the weak scale and a global minimum at which $< H >$ has a much larger value.

The vacuum decay from the false vacuum to the real vacuum was first calculated in 1976, using the $O(4)$ symmetric instanton solution. To understand the physics, and actually how the method was originally discovered, it is useful to consider the many-body theory of a superheated liquid. This was first studied by Langer in 1967. Water can be carefully heated above 100 degrees Centigrade at one atmospheric pressure in a clean apparatus.

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QUANTUM FIELD THEORY
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The superheated water may not boil for some time. It is in a metastable state. In order to boil, $O(3)$ symmetric bubbles must nucleate. What is the critical radius above which a bubble will grow and below which it will shrink and vanish? Let the bubble radius be R, the surface tension be S_1 and the latent heat of evaporation be ϵ. Such a bubble will have energy E given by

$$E = -\frac{4}{3}\pi R^3 \epsilon + 4\pi R^2 S_1 \tag{1}$$

Setting $dE/dR = 0$ give the critical radius $R_C = 2S_1/\epsilon$ above which the bubble will grow.

In 4-dimensional Euclidean spacetime the instanton has action

$$A = -\frac{1}{2}\pi^2 R^4 \epsilon + 2\pi^2 R^3 S_1 \tag{2}$$

which leads to $R_C = 3S_1/\epsilon$.

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The stationary value is $A_m = \frac{27}{2}\pi^2 S_1^4/\epsilon^3$ and the number of quantum tunnelings in Minkowski spacetime of volume V_U is given at lowest order by

$$N \sim (V_U R_C^{-4}) e^{-A_m} \qquad (3)$$

The scalar potential $V(H)$ has values $V(H_1)$ and $V(H_2)$ at the two minima and the volume energy of the bubble is $\epsilon = V(H_1) - V(H_2)$. Interpeting as a tunneling, the generalized surface tension is given by

$$S_1 = \int_{H_1}^{H_2} dH[2V(H) - \epsilon]^{1/2} \qquad (4)$$

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At one loop the effective potential has the form

$$V(H) = \frac{1}{2}\mu^2 H^2 - \lambda H^4 + BH^4 ln(H^2/v^2) \quad (5)$$

where the log term arises from the one loop diagrams. For boson loops B is positive. When fermion loops are included, B can become negative leading to a potential apparently unbounded below and no ground state. This was once used to put an upper bound on *e.g.* the top quark mass.

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Using the renormalization group to sum the leading logs, however, the runaway solution is seen to be an artifact of an approximation because under the RGE the top quark Yukawa coupling decreases at high energies. The effective potential can be treated using the RGE in the simpler form $V(H) = \lambda(H)H^4$. A generalized formula for the tunneling action emerges. This more powerful formulation is always used in the estimates which follow.

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3 STANDARD MODEL GROUND STATE

The decay of the metastable electroweak vacuum into the true ground state was first studied as a function of M_H including only boson loops. Another kind of instability was later emphasized where the presence of heavy fermion loops could make the effective potential unbounded from below. The conditions for vacuum stability were further improved by summing over leading logs in the effective potential. It was also emphasized in various subsequent works that the so-called unbounded potential is only an artifact since near the energy scale where instability is supposed to occur the top quark Yukawa coupling becomes small and/or new physics enters and the potential acquires a true vacuum at a value of the field much larger than the electroweak scale.

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Vacuum decay and Higgs mass

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The discovery of the H scalar with mass $M_H \simeq$ 126 GeV has precipitated a careful reevaluation of the electroweak vacuum stability and the result is especially interesting, that the vacuum is not perfectly stable. The result depends mainly on the mass of the top quark M_t and on M_H. This metastability of the vacuum depends sensitively on the values of these parameters. With the observed values $M_t = 173.36 \pm 0.65 \pm 0.3$ GeV and $M_H = 125.66 \pm 0.34$ GeV, the vacuum is metastable with an extremely long lifetime discussed below. If we keep one of the two fixed and vary the other, the sensitivity is that the vacuum would become absolutely stable if M_t were reduced to 171 GeV, or if M_H were increased to 130 GeV.

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This proximity to criticality is sufficiently striking that it is likely informing us profoundly about theoretical physics. It can be speculated that there is a statistical basis provided by a multiverse interpretation but such an idea seems untestable. Here we aim to exploit only facts which are on a firm basis.

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In two different cosmological futures can be considered: the ΛCDM model and a CDM model where the dark energy disappears. For these cases the lifetime of the electroweak vacuum for the observed values of M_H and M_t is respectively

$$10^{400} < \tau_{EW} < 10^{700} \quad \text{years} \tag{6}$$

for the ΛCDM model, and

$$10^{100} < \tau_{EW} < 10^{400} \quad \text{years} \tag{7}$$

for the CDM model.

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4 INSTANTON-INDUCED PROTON DECAY

According to the results of the Super-Kamiokande experiment, the lower bound on some proton decay partial lifetimes are $\tau(p \to e^+\pi^0) \geq 8.2 \times 10^{33}$ years and $\tau(p \to \mu^+\pi^0) \geq 6.6 \times 10^{33}$ years. In grand unified theories, *e.g.* minimal $SU(5)$, the lifetime was initially predicted as $\tau(p \to e^+\pi^0) \sim 10^{31}$ years which disagrees with experiment. We shall assume there is no grand unification which induces proton decay. As stated in the Introduction, we shall neglect also the effects of virtual black holes which could otherwise naively suggest $\tau_p \sim 10^{50}$ years.

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Perturbatively, the standard model conserves baryon number (B) and lepton number (L) but, as first noted by 't Hooft, non-perturbative instantons induce violations of B and L while preserving $(B - L)$. This leads to instanton-induced proton decay. The rate is suppressed by a factor

$$exp(-4\pi/\alpha_2) = exp(-4\pi \sin^2 \Theta_W/\alpha_{em}) \quad (8)$$

G. 't Hooft, Phys. Rev. Lett. **373,** 8 (1976).

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The lifetime for proton decay τ_p is proportional to the inverse of this rate and so

$$\begin{aligned} \tau_p &\propto exp(+4\pi \sin^2 \Theta_W / \alpha_{em}) \\ &\simeq exp(+371) \simeq 10^{+160} \end{aligned} \tag{9}$$

The determinant of fermion zero modes will affect only the prefactor so that to a zeroth approximation

$$\tau_p \sim 10^{160} \quad \text{years} \tag{10}$$

which is such a long lifetime that the difference from absolute stability may *prima facie* seem only academic. Nevertheless, we shall argue that the finite lifetime in Eq.(10) is very important.

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Note that even if the prefactor were calculated accurately for the amplitude of the proton decay, it would not so drastically change the estimate Eq.(10) to bring it outside the range permitted by Eq. (7). It is thus very reasonable to expect that the instanton-induced proton decay lifetime lies comfortably within the CDM range.

(By enlarging the SM gauge group, it might be possible to shorten considerably the instanton-induced proton lifetime. However, we limit ourselves strictly to the minimal SM.)

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Both τ_{EW} and τ_p are related to electroweak instantons, and both represent major decay processes in the extreme future of the Universe. What could be more natural than to set them equal?

$$\tau_{EW}(M_H) = \tau_p\,, \tag{11}$$

where τ_{EW} has a sensitive dependence on the Higgs mass M_H. Since τ_p is essentially fixed by the $SU(2)_L$ gauge coupling, the equality Eq.(11) amounts to a determination of M_H in terms of the proton lifetime.

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6 COSMOLOGICAL IMPLICATION

Comparison of τ_{EW} (CDM) with the instanton-induced proton lifetime then shows that the value $M_H \simeq 126$ GeV is required for this equality. If M_H were increased to *e.g.* 130 GeV, τ_{EW} would become infinite. If M_H were reduced to *e.g.* 122 GeV, one would find $\tau_{EW} \ll \tau_p$. The fact that this requires τ_{EW} (CDM) rather that τ_{EW} (ΛCDM) suggests that the dark energy will disappear before cosmic time $t = 10^{160}$ years, although a more careful analysis could sharpen this prediction about the extreme future of the Universe.

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As alluded to above, the true minimum is located at a value of the Higgs field orders of magnitude larger than for our metastable vacuum which is located at the electroweak scale. In the stable vacuum, quarks and leptons (and $W^{\pm}$, Z) will be supermassive and bound states very small compared to in the known universe, leading inevitably to a preponderance of black holes. On the other hand, if the protons have decayed long before the phase transition to the true ground state, as in the ΛCDM model, there will be no remaining quarks, only leptons $e^{\pm}$, ν and photons γ and, assuming the dark matter does not change, far less production of black holes. Such might not be the case if the proton decays when the phase transition to the true ground state occurs. This type of discussion may underwrite a rationale for the conjectured equality of lifetimes.

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The true ground state is stabilized by an incompletely understood mechanism and, as we have argued for the CDM case in a far distant future, it has vanishing vacuum energy since the dark energy has disappeared. Once gravity is included, and therefore absolute potential energy acquires significance, the decay is from the present vacuum which is dominated by dark energy with a relatively very tiny energy density to one with vanishing energy density, and it is tempting then to speculate even further that the mechanism that stabilizes the true vacuum also sets the energy gap between the two vacua equal to the dark energy density.

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7 DISCUSSION

Our conjectured equality equates the two longest time scales associated with the standard model. It has the advantage of using only facts which are known. We could hold M_H fixed, and vary M_t, but M_H is the more fundamental because the scalar is an exceptional particle in the standard model, being the only one with zero spin. If our present discussion is correct, it implies that the boson masses, rather than the fermion masses, are the more tractable.

Thank you for your attention.

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