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TESTING GUTS: WHERE DO MONOPOLES FIT? *

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1. Appetizer

It is impossible to resist the temptation to develop an anatomical analogy for the introduction to this talk. You have had the bare bones of monopole theory exposed to you.[1] My brief is now to enter the belly of the beast and discuss whether grand unified monopoles[2] (GUMs) should be regarded as a minor appendix to GUTs. We will indeed find that GUMs could provide crucial tests of GUTs, particularly through their possible propensity[3,4,5] to eat matter as they pass by it.

The skeletal outline of this talk is as follows: Section 2 describes why the inadequacies of the "standard model" of elementary particles impel some theorists[6] toward embedding the strong, weak and electromagnetic interactions in a simple GUT group, and explains why[7] the grand unification scale and hence the GUM mass are expected to be so large ($\gtrsim 10^{14}$ GeV). Section 3 goes on to describe some model GUTs, notably minimal SU(5)[6] and supersymmetric (susy) GUTs.[8] We introduce the grand unified analogues of generalized Cabibbo mixing angles,[9] relevant to the prediction of baryon decay modes in different theories as well as to the "Decay" modes catalyzed by GUMs.[10] Phenomenologies of conventional and susy GUTs are contrasted including the potential increase in the grand unification scale[11] as well as possible different baryon decay modes in susy GUTs.[12] It is emphasized that although the central hypothesis of GUTs — namely the existence of a primordial simple group broken down to include an electromagnetic U(1) factor at low energies — necessarily requires the existence of GUMs, nevertheless their masses are uncertain within the range $O(10^{16}$ to $10^{19})$ GeV. Section 4 discusses the phenomenology of GUMs, principally their ability[3,4,5] to catalyze baryon "decays." It is shown that while at distances outside the core of radius $O(1/m_X) \leq O(10^{-28})$ cm a gauge theory 't Hooft-Polyakov[2] GUM closely resembles a Dirac monopole,[13] nevertheless GUTs specify boundary conditions[14] at the core which cause monopole-fermion scattering to violate fermion number in general and baryon number in particular. The resulting large GUM-baryon $\Delta B \neq 0$ cross sections are then estimated,[10] and some possible experimental signatures[15,10] are mentioned (hierarchy of catalyzed "decay" modes, a possible "chain" of "decays" along the GUM's path, an apparent excess of Fermi motion due to recoil momentum O(300) MeV). Section 5 briefly introduces some of the astrophysical[16] and cosmological[17] constraints on GUMs, GUMs, which make it difficult to imagine ever seeing a GUM and may impose serious restrictions on GUT model-building via their behavior in the very early universe. We can get useful information about GUTs already from the abundance of GUMs as well as from their $\Delta B \neq 0$ interactions if they are ever seen. Finally, Section 6 summarizes the reasons why GUMs are crucial aspects and tests of GUTs.

2. Why GUTs?

The "standard model" of elementary particle physics is very unsatisfactory, possessing as it does a "random" gauge group $SU(3) \times SU(2) \times U(1)$ with three independent factors having three independent gauge couplings g_3, g_2 and g_1. Furthermore the known left-handed fermions sit in rather "random" looking representations of this group: each generation such as $(u, d, e^-, \nu_e)_L$ transforms as

$$\begin{cases} (3,2) & + \quad (\bar{3},1) \quad + \quad (\bar{3},1) \quad + \quad (1,2) \quad + \quad (1,1) \\ (u,d)_L & + \quad \bar{u}_L \quad + \quad \bar{d}_L \quad + \quad (\nu_e,e^-)_L \quad + \quad e^+_L \end{cases} \quad . \qquad (1)$$

Furthermore the U(1) hypercharge Y assignments are rather puzzling: they are all rational numbers so that the electromagnetic charges $Q_{em} = I_3 + Y$ are integer or fractional. Why are none of the hypercharges irrational or transcendental? This is another way of restating the old puzzle of the quantization of electromagnetic charge—why is $|Q_e/Q_p| = 1 + O(10^{-21})$? Even if one accepts as God-given all these fermion representation assignments, the "standard model" still has at least twenty arbitrary parameters, starting of course with the three gauge couplings g_3, g_2 and g_1 mentioned earlier.

A natural philosophy is to search for a simpler non-Abelian gauge group with a single gauge copuling. This was first tried for the weak and electromagnetic interactions alone, leaving the strong interactions to one side and postulating a guage theory based on $SU(3)_{color} \times G_{weak}$ with Q_{em} a generator of G_{weak}. This is anaesthetic because it still requires two gauge couplings, and furthermore it is difficult to arrange because when Q_{em} is a generator of a non-Abelian group one must have

$$\sum_{\text{representation}} Q_{em} = 0 \quad . \tag{2}$$

Since quarks and leptons have d'   t colors, the cancellation (2) must be arranged for   . separately

$$\sum_{\text{leptons}} Q_{em} = 0 = \sum_{\text{quarks}} Q_{em} \quad . \tag{3}$$

This is not possible with the known generations of quarks and leptons, which each contribute -1 to the left-hand sum and +1 to the right-hand sum. One possibility might be to add in additional particles to enforce the cancellation. Another possibility is to note that if one adds together the known quarks and leptons, then the condition (2) is satisfied.

Combining quarks and leptons in this way entails postulating a simple group containing both the strong and the electroweak interactions

$$G \supset SU(3)_{color} \times SU(2) \times U(1)_Y \qquad (4)$$

which therefore implies a single gauge coupling g from which the observed g_3, g_2 and g_1 derive. This is the GUT philosophy[6] we shall follow. Of course one may anticipate that there will be constraints on the fermionic $SU(3) \times SU(2) \times U(1)$ representations because they must all be representations of the underlying group G. In particular, the U(1) hypercharges will be constrained and charge quantization will be automatic. Now Q_{em} is a generator of the group, implying

$$\sum_{q+l} Q_{em} = 0 \qquad (5)$$

and all the fermion charges are related by simple Clebsch-Gordan coefficients.

The main obstacle to the GUT philosophy[6] outlined above is the fact that at present energies the different gauge couplings are grossly disparate:

$$g_3 >> g_2, g_1 \qquad (6)$$

Fortunately, this difficulty is resolved[7] by the realization that couplings vary logarithmically as a function of energy (momentum) scale. In particular, if no new physics intervenes, the SU(3) and SU(2) couplings approach each other (see Fig. 1) as

$$\frac{1}{\alpha_3(Q^2)} - \frac{1}{\alpha_2(Q^2)} = - \frac{\left(11 + \frac{N_H}{2}\right)}{12\pi} \ \ln\left(\frac{m_X^2}{Q^2}\right) \qquad (7)$$

where N_H is the number of light (mass $\lesssim O(100)$ GeV) Higgs boson doublets which is 1 in the minimal Weinberg-Salam model, and m_X is the energy scale Q at which $g_3 = g_2$ and grand unification becomes possible: $\alpha_{GUT} = \alpha_3 = \alpha_2$ ($\alpha_i \equiv g_i^2/4\pi$). Because of the logarithmic rate of variation (7) the grand unification scale m_X will be exponentially high:

$$\frac{m_X}{\Lambda_{QCD}} = \exp\left\{\frac{O(1)}{\alpha_{em}} + O(\ln \alpha_{em}) + O(1) + \ldots\right\} \qquad (8)$$

where Λ_{QCD} is the strong interaction scale of order 100 MeV to 1 GeV. As we will see in a moment, the grand unification scale must be $\geq 10^{14}$ GeV if baryons are to have lifetimes longer than about 10^{30} years as required by experiment. Moreover, m_X must be less than $O(10^{19}$ GeV) if we are to be able to get away without including gravitation in our GUTs. [This is because quantum gravity effects become O(1) at an energy $Q = O(m_P) = O(G_{Newton}^{-1/2})$.] The relation (8) then tells us[18] that the low energy α_{em} must lie in a relatively narrow range

$$\frac{1}{120} < \alpha_{em} < \frac{1}{170} \qquad (9)$$

if the GUT philosophy is to make any sense. The observed value of $\alpha_{em} = 1/137$ actually corresponds to $m_X \approx (10^{14}$ to $10^{15})$ GeV, encouraging us to hope that baryons may decay relatively soon, as we will see more quantitatively in a moment. It should however be emphasized that this analysis rests on the absurd and ludicrous assumption that no new physics intervenes between here and 10^{15} GeV (the "Desert Hypothesis"). If this is not valid the grand unification scale may be moved around, and we will see an example soon in the shape of susy GUTs. However, this possible variation in m_X does not vitiate the GUT philosophy of unification in a simple group at very high energy, which carries with it the necessary existence of GUMs with masses[1]

$$m_M \sim O\left(\frac{m_X}{\alpha_{GUT}}\right) \geq O\left(10^{16}\right)\text{GeV} \quad . \qquad (10)$$

There is one empirical test[7,19,20] of the GUT philosophy which a calculation of the effective weak neutral mixing angle θ_W at an energy scale Q:

$$\sin^2\theta_W\, Q^2 = \frac{3}{8}\left[1 - \frac{\alpha_{em}}{4\pi}\,\frac{110}{9}\,\ln\frac{m_X^2}{Q^2}\right] + \ldots \quad . \qquad (11)$$

In this formula the prefactor 3/8 is the symmetry value obtained from SU(5) Clebsch-Gordan coefficients, while the square bracket is a renormalization factor arising when the GUT symmetry is broken. Including higher order corrections[20] (the ... in equation (11)) we get

$$\sin^2\theta_W^{eff} = 0.215 \pm 0.002 \qquad (12)$$

for the effective value of $\sin^2\theta_W$ measured in experiments at present energies, if Λ_{QCD} = 100 to 200 MeV. The prediction (11) is relatively insensitive to the actual GUT, as long as it obeys the Desert Hypothesis. For comparison, the present experimental value is

$$\sin^2\theta_W^{eff} = 0.216 \pm 0.012 \qquad (13)$$

when radiative corrections are included,[21] in encouraging agreement with the prediction (12). The symmetry aspect of the prediction (11) results from the fact that hypercharge and $U(1)_{em}$ are embedded in a GUT. The renormalization correction results from setting $g_3 = g_2 = g_1$ at the same energy scale $Q = m_X$ as illustrated in Fig. 1. Hence the success of the prediction (12) "checks" both the GUT philosophy: $U(1)_{em}$, $Y \subset G$ and the large scale m_X at which it applies.

We now have several reasons for expecting GUMs. We know that quantization of magnetic charge h is to be expected in a theory with magnetic monopoles:

$$\frac{eh}{4\pi} = \frac{n}{2} \; ; \qquad n = 1, 2, \ldots \tag{14}$$

Conversely, one might have expected that the observed quantization of electric charge would be more easily understood in a theory with magnetic monopoles. Indeed, charge quantization emerges automatically when $U(1)_{em}$ is embedded in a simple group. All such theories harbor monopoles, and GUTs are examples of such theories. Therefore we expect to have GUMs.

3. What GUTs?

In order to specify the properties of GUMs more precisely we now go on to look at definite GUTs, starting off with the minimal version[6] of the minimal GUT group SU(5). This is broken down to the exact low energy $SU(3)_{color} \times U(1)_{em}$ symmetry as follows:

$$SU(5) \xrightarrow[10^{15}\ \text{GeV}]{} SU(3)_{color} \times SU(2) \times U(1)_Y \xrightarrow[10^{2}\ \text{GeV}]{} SU(3)_{color} \times U(1)_{em}$$

$$\begin{array}{ccc} \text{adjoint } \underline{24} \text{ of Higgs } \phi & \qquad & \text{adjoint } \underline{5} \text{ of Higgs } H \\ \Downarrow & & \Downarrow \\ m_{X,Y} & & m_{W,Z} \end{array} \tag{15}$$

Each fermion generation is assigned (somewhat inelegantly) to a reducible $\bar{\underline{5}} + \underline{10}$ representation of SU(5). For the first generation, neglecting generalized Cabibbo mixing, we have

$$\underline{\bar{5}} = \begin{pmatrix} \bar{d}_R \\ \bar{d}_Y \\ \bar{d}_B \\ \hline e^- \\ \nu_e \end{pmatrix}_L \begin{matrix} \left.\vphantom{\begin{matrix}a\\a\\a\end{matrix}}\right\} SU(3) \\ \left.\vphantom{\begin{matrix}a\\a\end{matrix}}\right\} SU(2) \end{matrix} \qquad \underline{10} = \frac{1}{\sqrt{2}} \underbrace{\begin{pmatrix} 0 & \bar{u}_B & -\bar{u}_Y & u_R & d_R \\ -\bar{u}_B & 0 & \bar{u}_R & u_Y & d_Y \\ \bar{u}_Y & -\bar{u}_R & 0 & u_B & d_B \\ -u_R & -u_Y & -u_B & 0 & e^+ \\ -d_R & -d_Y & -d_B & -e^+ & 0 \end{pmatrix}_L}_{SU(3)\qquad SU(2)} \begin{matrix} \left.\vphantom{\begin{matrix}a\\a\\a\end{matrix}}\right\} SU(3) \\ \left.\vphantom{\begin{matrix}a\\a\end{matrix}}\right\} SU(2) \end{matrix} \tag{16}$$

where we have indicated explicitly the subspaces on which the strong SU(3) and weak SU(2) subgroups act. We can read off immediately from the $\bar{5}$ representation (16) the traceless diagonal operator corresponding to electromagnetic charge:

$$Q_{em} = \mathrm{diag}\left(+\frac{1}{3},\ +\frac{1}{3},\ +\frac{1}{3},\ -1,\ 0\right) \quad . \tag{17}$$

This can be represented as a sum of the weak SU(2) generator T_3 and a traceless hypercharge Y:

$$Q_{em} = \left[T_3 = \mathrm{diag}\left(0,0,0,-\frac{1}{2},+\frac{1}{2}\right)\right] + \left[Y = \mathrm{diag}\left(\frac{1}{3},\frac{1}{3},\frac{1}{3},-\frac{1}{2},-\frac{1}{2}\right)\right] \quad . \tag{18}$$

Of relevance both to spontaneous baryon decay and to baryon "decays" catalyzed by GUMs is the structure of generalized Cabibbo mixing in GUTs.[9,19,22] Here we will just quote the results. In minimal SU(5) and related theories one can choose a fermion basis in such a way that:

- there is no mixing between elements of the $\underline{\bar{5}}$
- there is generalized Cabibbo mixing between elements of the $\underline{10}$ which is the Kobayashi-Maskawa matrix U_{KM} acting on rows and columns 1 to 4 relative to the fifth row and column:

$$\underline{10} = \frac{1}{\sqrt{2}} \left(\begin{array}{c|c|c} \bar{u}_{3\times 3} & u_{3\times 1} & d_{3\times 1} \\ \hline -u_{1\times 3} & 0 & e^{+} \\ \hline -d_{1\times 3} & -e^{+} & 0 \end{array} \right) \qquad (19)$$

- There are[9,19] also relative phases $e^{i\phi}$ between rows and columns 1 to 3 and the fourth row and column.

The appearance of the Cabibbo-Kobayashi-Maskawa matrix U_{KM} enables one to make predictions for Cabibbo-favored and -suppressed decay modes. The CP-violating phases $e^{i\phi}$ do not affect decay rates but they may have played a crucial rôle in Big Bang Baryonsynthesis. They may also give a nonintegral electric charge to the GUT monopoles.[23]

Baryon decay in minimal SU(5) is mediated by the exchange of the super heavy X and Y bosons which couple together the (1,2,3) and (4,5) of the fermion representations (16). The basic interaction is illustrated in Fig. 2(a), and the conventional model for the baryon decay amplitude is illustrated in Fig. 2(b). The amplitude is proportional to $1/m_X^2$ and hence the nucleon lifetime $\propto m_X^4$. Taking $m_X = (1 \text{ to } 4) \times 10^{14}$ GeV corresponding to $\Lambda_{QCD} = (100 \text{ to } 200)$ MeV one obtains a baryon lifetime

$$\tau_B = 10^{29\pm 2} \text{ years} \qquad (20)$$

Presumably m_X must be greater than 10^{14} GeV if baryons are to live longer than the present experimental limit.[24] The hierarchy of expected decay modes is[9,25]

$$\left.\begin{array}{lll} B \rightarrow & e\pi,\ e\rho,\ e\omega,\ \ldots & \text{(Cabibbo-favored)} \\ & > \nu\pi,\ \nu\rho,\ \ldots & (O(20)\ \%\ ) \\ & > \mu K & (O(10)\ \%\ ,\ \text{phase-space suppressed}) \\ & >> eK,\ \mu\pi,\ \ldots & \text{(few \%, Cabibbo-suppressed)} \end{array}\right\} \quad (21)$$

We will see in a moment how these decay patterns differ from those expected[12] in susy GUTs, and from the modes[10] of baryon "decay" catalyzed by GUMs.

Many conventional GUTs closely resemble minimal SU(5) in their predictions for the grand unification scale, $\sin^2\theta_W$, baryon decay modes, et cetera. However, recently much interest has developed in GUTs with $N=1$ global supersymmetry (susy GUTs).[8] The motivation for susy GUTs is an attempt to accommodate the required hierarchy of mass scales

$$m_W\left(m_H\right) = O\left(10^2\right)\ \text{GeV} << m_X = O\left(10^{15}\right)\ \text{GeV?} << ?\ m_P = O\left(10^{19}\right)\ \text{GeV} \quad . \quad (22)$$

The difficulty resolved by susy GUTs is that even if the hierarchy (22) is imposed on the Lagrangian at the tree level, it tends to be destroyed by radiative corrections such as the boson loops in Fig. 3(a) which give

$$\delta m_H^2\left(\delta m_W^2\right) = O\left(\alpha_{GUT}\right) m_B^2 >> m_H^2\left(m_W^2\right) \text{ if } m_B^2 \approx m_X^2 \quad . \quad (23a)$$

The solution proposed by susy is to invoke a cancellation by fermion loops as in Fig. 3(b). Because of their negative sign, if the bosons and fermions have similar couplings, equation (23a) gets replaced by

$$\left.\begin{aligned} \delta m_H^2\left(\delta m_W^2\right) &= O\left(\alpha_{GUT}\right)\left(m_B^2 - m_F^2\right) \\ &\approx m_H^2\left(m_W^2\right) \text{ if } \left|m_B^2 - m_F^2\right| \lesssim 1 \text{ TeV}^2 \end{aligned}\right\} \quad . \tag{23b}$$

The difference $|m_B^2 - m_F^2|$ is a measure of susy breaking for the particles appearing in the loops of Fig. 3. If it is sufficiently small, then the radiative corrections to m_H^2 and m_W^2 are sufficiently small for their values of $O(100\text{ GeV})^2$ to seem "natural." For the cancellations (23b) to work, there must be bosonic partners for all known fermions (and vice versa) with *essentially identical* couplings, as seen in the following table:

Spin	Particles		
1	vector boson		
½	gaugino	quark, lepton	shiggs
0		squark, slepton	Higgs

No known particles can be supersymmetric partners of each other. Therefore a susy GUT contains at least twice as many particles as a conventional GUT, and in general even more since it requires at least two light Higgs doublets: $N_H \geq 2$.

The new particles with masses << 10^{15} GeV populate the desert and therefore modify the conventional GUT phenomenology. The rate of approach (7) of the SU(3) and SU(2) gauge couplings becomes significantly slower,[11]

$$\frac{1}{\alpha_3(Q)} - \frac{1}{\alpha_2(Q)} = + \frac{\left(9 + \frac{3}{2} N_H\right)}{12\pi} \ln \frac{Q^2}{m_X^2} \tag{24}$$

implying an increase in the grand unification scale

$$m_X \to m_X \times O(40) \sim 10^{16}\ \text{GeV} \qquad (25)$$

in the most economical susy GUTs. There are more complicated variants[26] with more heavily populated deserts whose grand unification scale may be as large as 10^{19} GeV. Maintaining the successful (13) prediction (12) of $\sin^2\theta_W$ can also be a problem:

$$\sin^2\theta_W^{eff} = 0.236 \pm 0.002 \qquad (26$$

in the most economical susy GUTs.[11,12] One might naively have expected the increase in the m_X to increase the baryon lifetime in a susy GUT. However, this is not necessarily the case as there is[27] a new class of diagrams like that in Fig. 4 which can give an interaction amplitude comparable[12] with that from Fig. 2(a), and hence a similar baryon lifetime to the estimate (20). In the simplest susy GUTs, though, the hierarchy of baryon decay modes is different[12] from that (21) in non-conventional GUTS.

$$\left.\begin{array}{lll} B \to & \bar{\nu}K & \text{(favored by Cabibbo angles and quark mass factors)} \\ & \gg \bar{\nu}\pi & \text{(suppressed by quark mass factors)} \\ & \gg \mu^+\pi & \text{(Cabibbo suppressed)} \\ & \gg e^+K & \text{(Cabibbo suppressed)} \\ & \gg e^+\pi & \text{(suppressed by quark mass factors)} \end{array}\right\} \qquad (27)$$

It should be emphasized that while (26) and (27) are the predictions of the most economical susy GUTs, the ability to fix particle masses in such a way that they are not disturbed by radiative corrections (23) means that one can populate the desert in such a way as to vary the predictions of $\sin^2\theta_W$, m_X and the baryon decay modes almost at will. For example, there are susy GUTs where baryons decay predominantly into μ^+K or even into old-fashioned $e^+\pi$.[25]

The moral of this rapid review of GUTs is that within the general GUT philosophy[6] there are considerable phenomenological ambiguities. While there are "canonical" conventional and susy GUT predictions for m_X (and hence the monopole mass $m_M = m_X/\alpha_{GUT}$) and for the hierarchy of baryon decay modes (to be contrasted with the "decay" modes catalyzed by GUMs) one should be alive to other possibilities. GUM hunters should be prepared for GUM masses anywhere between 10^{16} and 10^{19} GeV, and should be aware that the hierarchy[10] of baryon "decay" modes catalyzed by GUMs may not be specific: they should keep their eyes open for other signatures as well.

4. GUMs in GUTs

Previous speakers[1] have shown you that monopoles arise inevitably[2] in theories where a simple non-Abelian group is broken down to give $U(1)_{em}$ at low energies (large distances). Therefore we expect grand unified monopoles (GUMs) in GUTs. At radii much larger than the size of the monopole core (of order m_X^{-1} in GUTs) non-Abelian 't Hooft-Polyakov[2] monopoles look just like Dirac[13] monopoles corresponding to some U(1) subgroup of the exact low-energy $SU(3)_{color} \times U(1)_{em}$ gauge group. The corresponding gauge interactions of the first generation of fermions are

$$\mathcal{L} = g_3\left[\bar{u}\not{G}u + \bar{d}\not{G}d\right] + e\left[\frac{2}{3}\bar{u}\not{A}u - \frac{1}{3}\bar{d}\not{A}d - \bar{e}\not{A}e\right] \qquad (28)$$

where G and A stand for gluon and photon fields respectively.

A conventional Dirac monopole would sit in the $U(1)_{em}$ subgroup and have a magnetic charge h obeying the Dirac quantization condition

$$eh = 2\pi \quad . \tag{29}$$

This is not a possible monopole for us, however, since the condition (29) means that quarks which have (28) fractional charge can detect its string. This snag can be evaded either by going to a monopole with a magnetic charge three times larger, which is expected to be mcuh heavier and so to be unstable against decay into lighter monopoles and hence cosmologically irrelevant, or else by adding to the magnetic charge h (29) an additional chromomagnetic charge corresponding to some U(1) subgroup of $SU(3)_{color}$. All such options are gauge equivalent to looking at monopoles sitting in the U(1) subgroup generated by the λ_8 of color SU(3), and the minimal GUM has chromomagnetic charge h_3:

$$g_3\, h_3 = 2\pi \begin{pmatrix} \frac{1}{3} & & 0 \\ & \frac{1}{3} & \\ 0 & & -\frac{2}{3} \end{pmatrix} \tag{30}$$

as well as the $U(1)_{em}$ charge h (29). It is easy to check that all the first generation left-handed fermions have an integer charge g of the U(1) generated by (λ_8, Q_{em}):

$$g = \left\{ \begin{array}{ll} +1: & u_{R_L}\,,\; u_{Y_L}\,,\; \bar{d}_{B_L}\,,\; e^+_L \\ 0: & u_{B_L}\,,\; d_{R_L}\,,\; d_{Y_L}\,,\; \bar{u}_{B_L}\,,\; \bar{d}_{R_L}\,,\; \bar{d}_{Y_L}\,,\; \nu_L \\ -1: & \bar{u}_{R_L}\,,\; \bar{u}_{Y_L}\,,\; d_{B_L}\,,\; e^-_L \end{array} \right\} \tag{31}$$

and hence cannot see the string of the GUM with the charges (h_3, h) given by (29,30).

It has been pointed out[14] that fermions may change their nature when scattering off a Dirac monopole in the S-wave. One way to see this is to recall that a particle of electric charge g moving in the field of a monopole of magnetic charge h has an associated angular momentum

$$\underline{J} = \frac{gh}{4\pi} \underline{\hat{r}} \quad . \tag{32}$$

This acquires a sign change when the fermion passes through the monopole core, because $\underline{\hat{r}} \to -\underline{\hat{r}}$. Angular momentum can be conserved if there is a simultaneous change of sign $g \to -g$. In general this requires a change in the flavor of the fermion (cf., the charge assignments (31) of conventional fermions). There is an ambiguity[14] in how one pairs up fermions into doublets (f, f') with equal and opposite electric charges relative to the monopole of interest, which then determines how flavor is violated in scattering events. This ambiguity cannot be resolved in the context of old-fashioned Dirac monopole theory. It can only be resolved by specifying fermion boundary conditions at the core of the monopole, which can be done[10] in the context of a GUT. We recall that our monopole which looks Dirac-like at large distances is expected to have a regular core specified by our choice of GUT. Our (λ_8, Q_{em}) U(1) group must be embedded in some SU(2) subgroup of our GUT. This means that there must be a non-Abelian gauge generator coupling our doublets (f, f'), and hence these transitions must have definite color and electromagnetic charge corresponding to the $SU(3) \times U(1)$ transformation properties of a massive gauge boson. The only consistent doublet assignments for the first generation fermion, (31), are

$$\begin{pmatrix} u_R \\ \bar{u}_Y \end{pmatrix}_L , \quad \begin{pmatrix} u_Y \\ \bar{u}_R \end{pmatrix}_L , \quad \begin{pmatrix} e^+ \\ d_B \end{pmatrix}_L , \quad \begin{pmatrix} \bar{d}_B \\ e^- \end{pmatrix}_L . \qquad (33)$$

We must allow for "Cabibbo" mixing permutations of these doublets when one takes into consideration multiple generations, a point we return to[10] in a moment. Using the doublets (33) and their friends involving heavier fermions one can construct effective interactions involving even numbers of fermions:

$$(ff'), \quad (ff'f''f'''), \quad (6f), \quad (8f), \quad \ldots \quad . \qquad (34)$$

The interesting interactions have $\Delta Q_{em} = 0$, so that they do not involve monopole ↔ dyon transitions but can be catalyzed by CUMs alone. In general these $\Delta Q_{em} = 0$ interactions will have ΔB, $\Delta L \neq 0$.

So far we have not invoked any specific CUT: let us now see what happens if we embed our monopole in SU(5). One possible SU(2) subgroup of SU(5) that we can exploit for the non-Abelian core of our CUM is

$$\underline{I} \equiv \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \multicolumn{2}{c}{} & 0 \\ 0 & 0 & \multicolumn{2}{c}{\underline{\tau}} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \qquad (35)$$

and alternatives involve replacing the blue (third) color by either yellow or red. We now see that the possible doublets of fermions are determined by the generalized "Cabibbo" mixing analysis[9,12] discussed in Section 3 (see equation (19)). The facts that there is no mixing of fermions in the $\underline{\bar{5}}$ representations and no relative mixing between the third and fourth rows of the $\underline{10}$ representations, but only phase factors $e^{i\phi}$, mean that the prospective doublets (33) are essentially correct apart from phase factors, with a similar structure for heavier generations. For particles weighing less than 1 GeV:

$$\begin{pmatrix} u_R \\ \bar{u}_Y e^{i\phi} \end{pmatrix}_L , \begin{pmatrix} u_Y \\ -\bar{u}_R e^{i\phi} \end{pmatrix}_L , \begin{pmatrix} \bar{d}_B \\ e^- \end{pmatrix}_L , \begin{pmatrix} e^+ \\ -d_B \end{pmatrix}_L , \begin{pmatrix} \bar{s}_B \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \mu^+ \\ s_B \end{pmatrix}_L . \tag{36}$$

These yield the following effective interactions[3,10,15] which may be particularly relevant to low-energy GUM collisions with baryons:

$$\left.\begin{array}{ll} 2f: & \bar{d}_B d_B , \quad \bar{u}_Y u_Y , \quad \bar{u}_R u_R , \quad e^+ e^- \\ 4f: & \bar{u}_Y \bar{d}_B \bar{u}_R e^+ , \quad u_R e^- u_Y d_B , \quad \bar{u}_Y \bar{s}_B \bar{u}_R \mu^+ , \quad u_R \mu^- u_Y s_B \\ 6f: & u d u e^- \mu^+ \mu^- , \quad u e^- u s e^+ \mu^- \end{array}\right\} . \tag{37}$$

We see that the 4 and 6 fermion interactions in (37) have $\Delta B = \pm 1$ (while conserving $B - L$) and therefore expect them to lead to $\Delta B \neq 0$ GUM-Baryon cross sections. Condensates like (37) are expected to exist in any region of space where the GUM looks like an apparent Dirac monopole with the magnetic and chromomagnetic charges (29,30). We expect the chromomagnetic field to extend as far as the confinement radius of order 1 fermi. Therefore the $\Delta B \neq 0$ cross section may have the magnitude of a conventional strong-interaction cross-section. One of the 4 or 6 fermion interactions (37) could take place whenever the GUM overlaps with a baryon. Since the duration of the overlap during a collision is given by a $1/\beta$ flux factor at low velocities β, we parametrize the cross section in the form

$$\sigma_{\mathrm{GUM}\,\mathrm{B}\neq 0} \approx \frac{1}{\beta}\ \frac{\sigma_0}{1\ \mathrm{GeV}^2} \tag{38}$$

at low velocities, where σ_0 is a dimensionless reduced cross-section factor. It is then a problem in strong interaction phenomenology to estimate σ_0. *A priori* one might imagine[3,5] that it could be O(1), but quite honestly we do not know at the present time how big it might be. Since the forms of the $\Delta B \neq 0$ interactions (37) are similar to those due to X,Y boson exchange in conventional GUTs, one way[10] of estimating σ_0 (see Fig. 5) is by analogy with the conventional calculation of the spontaneous baryon decay rate $\Gamma(B \to e^+X)$ mediated by X and Y boson exchange (cf., Fig. 2). One then estimates

$$\sigma_{\mathrm{GUM}\,\mathrm{B}\neq 0} \approx \frac{1}{\beta}\ \frac{\hat{\Gamma}\left(B \to e^+X\right)}{1\ \mathrm{GeV}^3} \quad , \tag{39}$$

where $\hat{\Gamma}$ is obtained from Γ by the replacement

$$\frac{g^2}{m^2_{X,Y}} \to \left(\frac{1}{4\pi^2}\right)^2\ \frac{1}{1\ \mathrm{GeV}^2} \quad . \tag{40}$$

The factors of 1/1 GeV in equations (39) and (40) come from dimensional analysis. The factors of $1/4\pi^2$ in equation (40) come from Rubakov's analysis[3] of fermion condensates around a monopole. Keeping track of all the factors of $1/2\pi$ that we can identify, we guess[10] wildly that

$$\sigma_0 = O\left(10^{-4}\right) \times O\left(10^{\pm 2}\right)\ ? \tag{41}$$

In this case an astrophysically plausible slow-moving GUM with $\beta = O(10^{-3})$ might have a B-violating cross section

$$\sigma_{\mathrm{GUM}\,B\neq 0} = O\left(10^{-28}\right)\ \mathrm{cm}^2\ ?\ ? \tag{42}$$

While keeping this possibility in mind, we will try to keep σ_0 as a free parameter in the subsequent analysis.

One can deduce[10] from equation (37) a likely hierarchy of baryon "decay" modes catalyzed by GUMs. This is

$$\left.\begin{array}{lll} B \to & e^+ \text{ pions} & (\text{"Cabibbo"} - \text{favored}) \\ \gg & \mu^+ K & (\text{suppressed by phase space, quark mass factors?}) \\ \gg & e^+\mu^+\mu^-(\pi), \mu^+e^+e^-K & (\text{suppressed by condensate factors}) \\ B \not\to & \bar{\nu} K & (\nu \text{ has no magnetic charge}) \\ & e^+K, \mu^+\pi & (\text{"Cabibbo" disallowed}) \end{array}\right\} \tag{43}$$

This is to be compared with the conventional GUT hierarchy (21) and the simplest susy GUT predictions (27). There are some differences which may serve as signatures for baryon "decays" catalyzed by GUMs. Other possible experimental signatures include the possibility of a three-momentum transfer to the "decay" products. There is no reason why the three-momentum transfer should be zero and we might expect it to be of conventional strong interaction magnitude

$$|\Delta \underline{q}| = O(300)\ \mathrm{MeV}\ ? \tag{44}$$

This would act in the same way as conventional Fermi motion for a decaying nucleon in a heavy nucleus, causing the baryon "decay" products not to come out back-to-back. It might be difficult to conclude that there was an excess of Fermi momentum of order (44), except possibly if one were looking for baryon "decays" in very light nuclei such as hydrogen. One also expects a net energy transfer

$$|\Delta E| = O(\beta)\ \mathrm{GeV} \tag{45}$$

to the baryon "decay" products, which is undetectable for slow monopoles. A potentially interesting possibility[15] is the observability of multiple baryon "decays" occurring in a chain across a detector. One expects a mean free path between catalyzed events of

$$\lambda = \frac{43\mathrm{m}}{\rho}\left(\frac{\beta}{\sigma_0}\right) \tag{46}$$

where ρ is the matter density in gm/cc. This corresponds to a mean free time between events of

$$\tau = \frac{\lambda}{\beta} = \frac{0.14}{\rho\sigma_0}\ \text{microseconds} \tag{47}$$

which would be O(1) milliseconds if $\sigma_0 = O(10^{-4})$. Baryon decay detector designers should bear this point in mind. Several of the early detectors[28] had electronics dead times of about a millisecond after each baryon decay candidate occurred while it was being put on tape. For this reason they would not have been sensitive to "decays" in coincidence within the time difference (47). The NUSEX and IMB experiments are presently considering modifications of their electronics so as to avoid this dead time.

Figure 6 exhibits[10] the sensitivity of possible experimental searches for Baryon-number violating GUM interactions using baryon decay experiments. We see that they can see GUM-catalyzed "decays" if the GUM flux is within a few orders of magnitude of Cabrera's limit,[29] and that they also have a fair chance of seeing double "decays."

5. Astrophysical and Cosmological Limits on GUMs

Since these are the subjects of two full sessions at this Workshop, I will not do much more than just remind you what issues[16,17] are involved. First of all, there are unimpeachable constraints[30,31] on the density and hence flux of GUMs following from upper limits on the mass density in the Universe [relevant if the local GUM velocities β are larger than $O(10^{-3})$ in which case monopoles are not confined to galaxies], or from the missing mass in the galaxy [relevant if $O(10^{-4}) < \beta < O(10^{-3})$ in which case monopoles are not bound in the solar system but are confined to galaxies]. Then there are more arguable constraints on the flux of monopoles due to the persistence of the galactic magnetic field.[32,33] Normally one believes that monopoles act as a drain on the galactic field energy as it accelerates them,[32] but there is a controversial minority viewpoint[33] that monopole plasma oscillations might actually be responsible for generating the galactic magnetic field, in which case the GUM flux could (should) be considerably larger. Another suggestion[34] for making large fluxes of GUMs more tolerable is that their density may be locally enhanced due to our proximity to a local source, most probably the Sun. This might work if $\beta < O(10^{-4})$, but it is not clear how a solar cloud of monopoles could have formed, nor how much local enhancement in the flux could be attained. Finally there are distinctly less reliable constraints on the GUM flux which are conditional on their having large $\Delta B \neq 0$ cross sections. An important constraint comes from neutron stars.[35,10,36] GUMs could get stuck in them and "eat" their baryons, producing energy which is eventually thermalized and radiated as X-ray or ultraviolet light. Upper limits[37] on the flux of X rays either from known point-source neutron stars or from a diffuse background of older unresolved neutron stars give quite stringent limits on the product of GUM flux F and dimensionless reduced cross section σ_0. The most conservative constraint from the X-ray background is[10]

$$F\sigma_0 < 6.6 \times 10^{-15}\, \beta^2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1} \quad . \tag{48}$$

This constraint has been derived assuming that we and the neutron star are both bathed in a continuing galactic flux, and neglects the possibility[34] that there may be local flux enhancements around stars when $\beta < O(10^{-4})$. In this case the neutron star limit may be somewhat relaxed.[10] The various astrophysical constraints are of varying relative importance for different GUM masses. Figure 7 shows versions[10] of the different astrophysical constraints for masses of 10^{16} GeV (Fig. 7(a)) and of 10^{19} GeV (Fig. 7(b)). Also shown is the present constraint[10,15] from baryon decay experiments

$$F\sigma_0 < 2 \times 10^{-12}\, \beta\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1} \tag{49}$$

and the maximum possible sensitivity of future baryon decay experiments. While the astrophysical constraints make it difficult to imagine seeing $\Delta B \neq 0$ interactions catalyzed by GUMs, it is not impossible at least if $\beta < O(10^{-4})$ and the GUM mass is close to the Planck mass. As also shown in Fig. 7, it may also be possible to detect O(100) MeV neutrinos originating from $\Delta B \neq 0$ processes in the Sun.[3,34]

For completeness, I will also mention the problem[17] of the cosmological production and abundance of GUMs, emphasizing that the possibility of an observable GUM flux is not excluded. Conventionally[38,39] one expects O(1) GUM in every horizon volume at the epoch when GUMs were formed at a critical temperature $T_c \geq O(10^{15})$ GeV. This gives many more GUMs than are allowed by the present mass density of the Universe, and to compound the problem it seems unlikely[30] that monopole-antimonopole annihilation could have reduced the original GUM abundance to an acceptable level today. An attractive way out of this impasse is the new inflationary cosmology,[39] according to which the entire visible Universe sits within one bubble of correlated Higgs fields and the closest topological knot corresponding to a GUM is (much) more than 10^{10} light years away. (Un)fortunately the new inflationary Universe has difficulties with the fine-tuning of parameters[40] and the magnitude of fluctuations.[41] These can be alleviated or resolved if the underlying theory is supersymmetric[40] and if the magnitude V of the Higgs vacuum expectation value driving the inflation is close to the Planck mass.[42] This is fine for solving the purely cosmological problems which inflation is supposed to cure, but the GUM abundance problem persists if $V \gg m_X$ ("primordial inflation"). It may be possible to resolve the GUM problem if primordial inflation is combined with one of the other "solutions" to the GUM problem discussed a while ago. These are "supercosmology" in which the GUT phase transition is delayed to $T_c = O(10^{10})$ GeV resulting in larger horizon volumes and hence perhaps fewer monopoles,[43] or a second-order GUT phase transition in which the monopole abundance may be thermodynamically suppressed,[44] In either of these cases the abundance of GUMs may avoid being unobservably small.[42] Therefore GUM hunters should not allow themselves to be discouraged by inflationary cosmologists! However, it is clear that getting an acceptably small abundance of GUMs, or still better an observably large flux, imposes nontrivial cosmological constraints on the nature of the GUT. This is yet another way in which monopoles can be used to test and discriminate between different GUTs.

6. Dessert

We have seen that gauge theories do not expect monopoles[2] with low masses ($\lesssim O(10)$ TeV), but that one does expect grand unified monopoles (GUMs) with masses $\gtrsim O(10^{16})$ GeV. GUMs are unavoidable consequences of the GUT philosophy[6] of embedding $U(1)_{em}$ in a simple group along with all the other interactions. The mass of the monopole tells us about the grand unification scale: $m_X = \alpha_{GUT}\, m_M$. There is the exciting possibility[3,4,9] that GUMs may catalyze $\Delta B \neq 0$ interactions with a strong interaction cross sectior If so, observation of the modes of catalyzed "decay" could tell us about the grand unified generalized Cabibbo mixing.[9] The production or lack of production of GUMs in the early Universe tells us about the desired behavior of GUTs at temperatures $O(m_X)$. GUMs could therefore provide us with crucial tests of GUTs. Figure 8 shows the ideal, ultimate GUM detector. It contains a more-or-less conventional baryon decay detector, hopefully made of light material so that "anomalous Fermi motion" can be detected. Around this is an ionization or scintillation detector, hopefully sensitive to B as low as 10^{-4}. Around this is an induction coil looking for flux jumps due to GUMs passing through. Also shown in Fig. 8 is a dream event in which the coil flux jumps, the ionization detector fires and there is a chain of catalyzed baryon "decays." Such an event would certainly probe the viscera of our GUTs.

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Figure Captions

Fig. 1. An illustration of the GUT philosophy. The SU(3), SU(2) and U(1) couplings come together at an energy scale $m_X = O(10^{15})$ GeV if the desert is unpopulated. This grand unification scale appears to be significantly less than the Planck mass of order 10^{19} GeV at which quantum gravity effects are O(1).

Fig. 2. (a) Lowest order heavy gauge boson exchange diagram giving rise to baryon decay in conventional GUTs, and
(b) the most popular way of estimating the baryon decay rate.

Fig. 3. (a) Boson loop diagrams which contribute positively to δm_H^2, and
(b) fermion loop diagrams which contribute negatively and cancel in a supersymmetric theory.

Fig. 4. Lowest order loop diagram contributing to baryon decay in a supersymmetric GUT, showing how the dimension 5 $\widetilde{f}\widetilde{f}ff$ operator is related to superheavy Higgs H and shiggs $\tilde{H}$ exchange.

Fig. 5. Sketch of mechanism for baryon "decay" catalyzed by a GUM. Two quarks coming within one fermi of the GUM core may be sucked into it and change their flavors in a similar way to that in Fig. 2.

Fig. 6. Indication of the capabilities of baryon decay experiments to search for B "decays" catalyzed by GUMs.[10] The probable (?) range of β and the possible (?) range of the $\Delta B \neq 0$ cross-section strength σ_0 (38) are indicated. Experiments can observe a catalyzed "decay" in the region marked 1E if GUMs have the Cabrera flux.[29] In the region 2E two events can occur within the same apparatus. The solid lines refer to the NUSEX experiment, the dashed lines to the IMB experiment.

Fig. 7. Plots of the astrophysically allowed regions for the GUM flux F (measured in $cm^{-2}\ s^{-1}\ sr^{-1}$) for different GUM velocities and masses (a) 10^{16} GeV and (b) 10^{19} GeV.[10] Catalyzed B "decays" and O(100) MeV neutrinos from the Sun (if GUMs stop inside it) are detectable above the indicated lines corresponding to an apparent "lifetime" of 10^{33} years and $F_\nu = 1\ cm^{-2}\ s^{-1}\ sr^{-1}$. The astrophysical bounds come from neutron stars (NS), the galactic magnetic field (GB), the density of the Universe (DU) and the missing mass in the galaxy (MM). Also shown on (b) is the upper limit on $F\sigma_0$ coming from present-day baryon decay exr . (BD).

Fig. 8. r the ideal, ultimate GUM detector. It includes an i... .on coil and an ionization or scintillation detector mounted around a conventional baryon decay detector. Also shown is a dream GUM event.

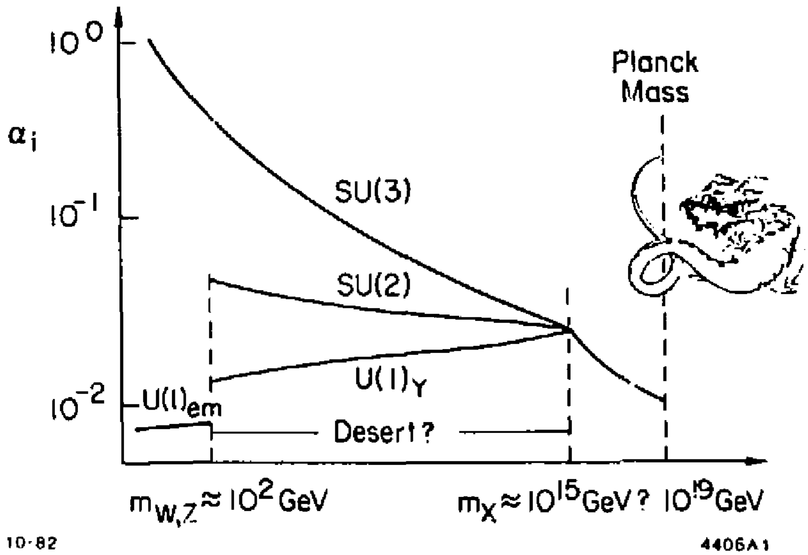

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Fig. 1

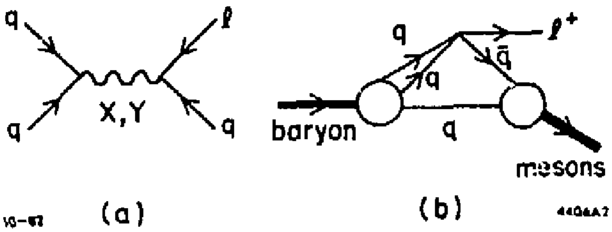
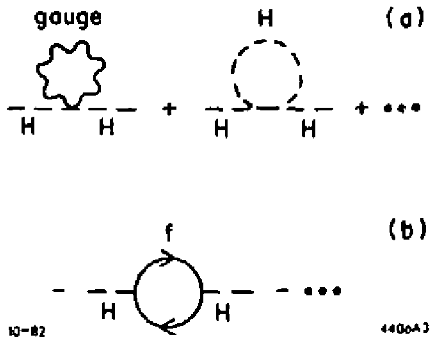


Fig. 2



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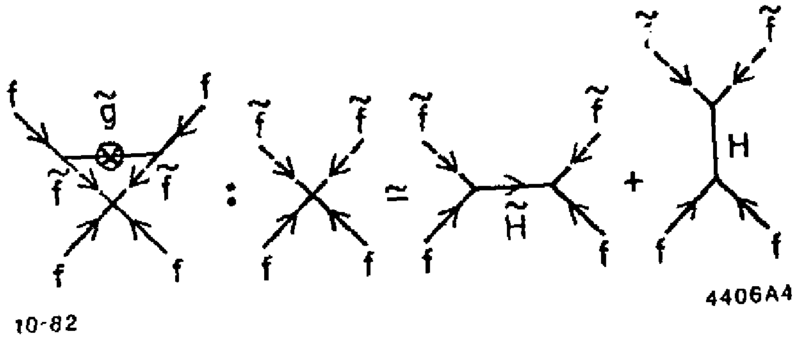
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Fig. 4

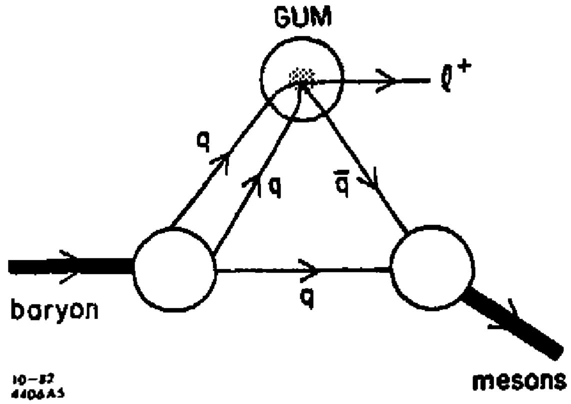
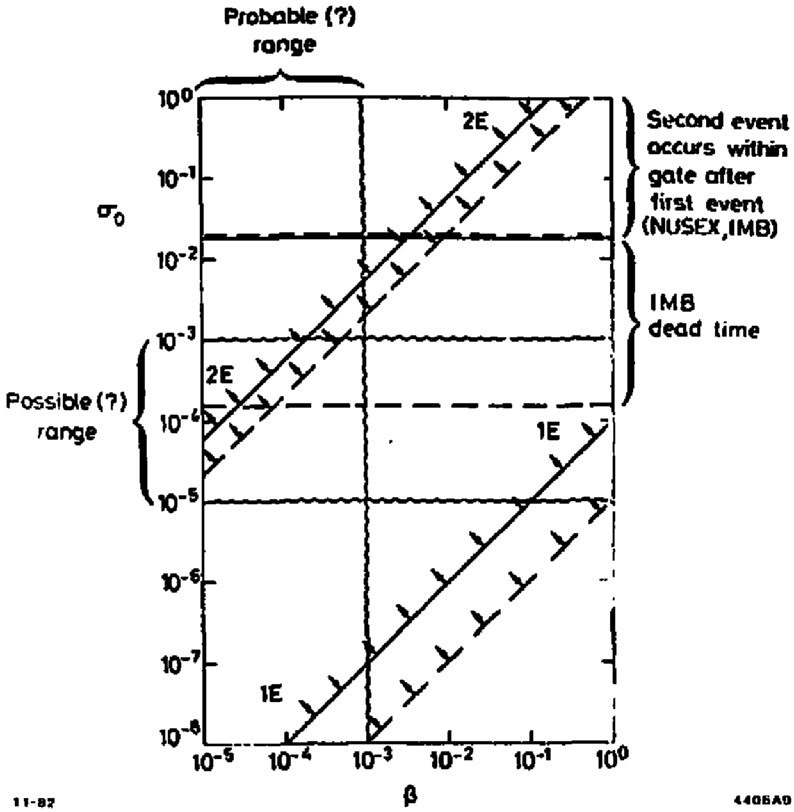


Fig. 5



Probable (?)
range
Second event
occurs within
gate after
first event
(NUSEX,IMB)
IMB
dead time
Possible (?)
range
σ_0
2E
2E
1E
1E
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
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10^0
β
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Fig. 6

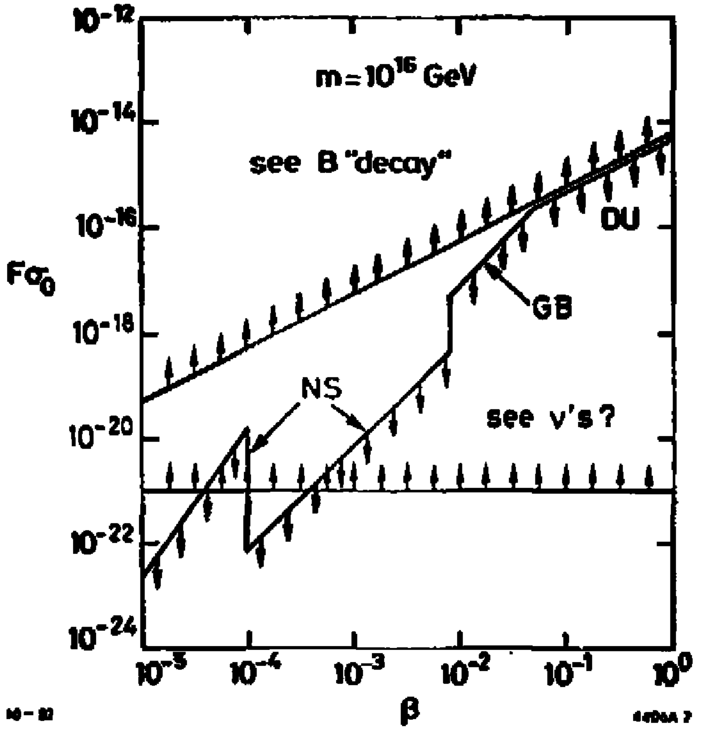

Fig. 7(a)

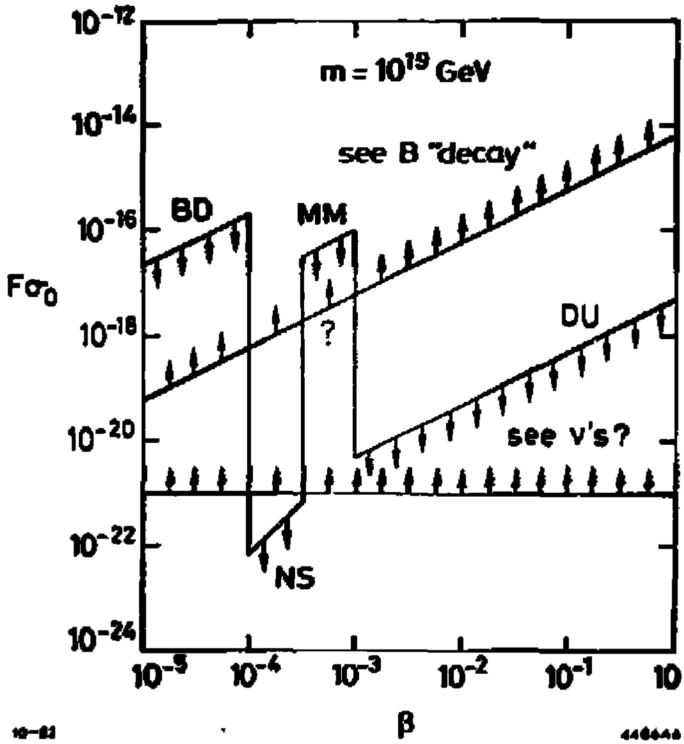
m = 10^19 GeV
see B "decay"
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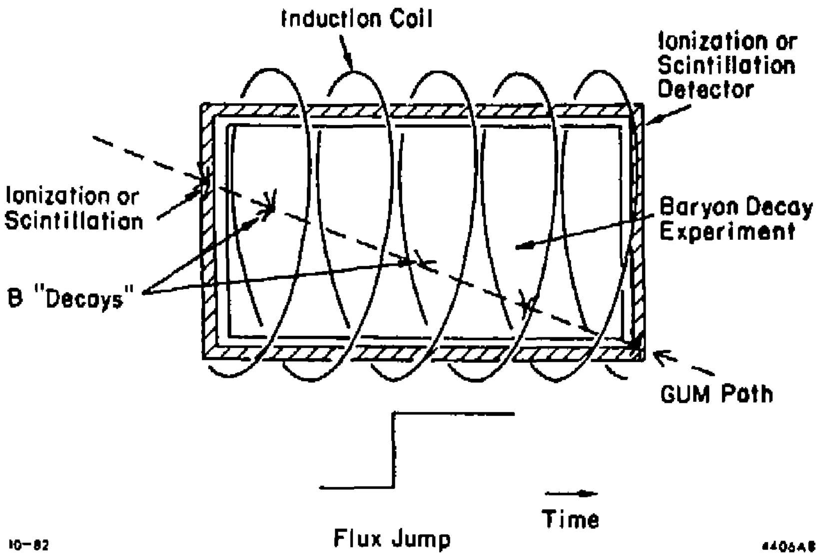
Fig. 7(b)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10-82
4406A8

Fig. 8