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BARYON NUMBER VIOLATION CATALYZED BY GRAND UNIFIED MONOPOLES

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A B S T R A C T

It has been recognized for some time that grand unified monopoles may catalyze $\Delta B \neq 0$ processes. We obtain model-independent upper bounds on the rates for such reactions from the survival of the baryon number generated in the early Universe and from present-day baryon stability. These constraints are compatible with recent estimates of large baryon number violating monopole cross-sections, but a monopole flux close to present experimental upper limits could be detectable in forthcoming baryon decay experiments. We mention signatures for monopole-induced baryon "decay" and point out that it could be used to solve the "energy crisis".

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Grand unified theories (GUTs) ¹⁾ predict baryon decay and the existence of magnetic monopoles ²⁾. If either of these were discovered it would be strong evidence for the validity of GUTs. Unfortunately the baryon lifetime is rather model-dependent ¹⁾, and the expected flux of grand unified monopoles (GUMs) is either embarrassingly high ³⁾ or else depressingly low ⁴⁾. Our experimental colleagues have established ^{5),6)} a lower limit on the baryon lifetime of about 3×10^{30} years, and there are some unconfirmed candidate events ⁶⁾ lurking just outside this limit. There are strong upper limits on the flux of "fast" [$\bar{v} > 0(10^{-3})$] monopoles ⁷⁾, less stringent limits on the flux of "slow" monopoles ⁸⁾, and a recent unconfirmed monopole candidate ⁸⁾. It has been known for some time ⁹⁾ that GUMs would have baryon number violating interactions with ordinary matter, but it used to be thought that the cross-section would be very small because of the small geometric size of GUMs. However, Rubakov ¹⁰⁾ has argued that $\Delta B \neq 0$ GUM cross-sections may be comparable with conventional strong interaction cross-sections. He has found that monopoles are surrounded by a strong condensate of fermion pairs of characteristic radius m_f^{-1} , and that the collisions of conventional fermions with this condensate generally violate baryon number. Rubakov's observation has recently been supported by an analysis due to Callan ¹¹⁾. The combination of large $\Delta B \neq 0$ GUM-matter cross-sections and a possibly large flux of GUMs is heady stuff : perhaps one will be able to verify simultaneously both the exciting predictions of GUTs mentioned in our opening sentence.

In this paper we first check that the $\Delta B \neq 0$ GUM cross-sections suggested by Rubakov ¹⁰⁾ are not large enough to have eradicated the baryon number of the Universe previously generated ¹²⁾ by GUTs. We then study the constraint on the product of GUM flux and $\Delta B \neq 0$ cross-sections imposed by the observed stability of nucleons, and show that baryon "decay" catalyzed by GUMs should be observable in the near future if the GUM flux approaches present experimental limits ^{7),8)} as seen in the Figure. We then analyze the baryon "decays" catalyzed by GUMs in the minimal $SU(5)$ GUT ¹³⁾ and mention possible signatures. These include $p, n \rightarrow e^+ + \text{pions}$ (not $\mu^+ + \text{pions}$, $e^+ + \text{strange particles}$, $\mu^+ + \text{strange particles}$ or $\bar{\nu} + X$), and the possibility of $p, n \rightarrow e^+ \pi (\mu^+ \mu^-)$ proposed previously by Rubakov ¹⁰⁾. Finally, we point out that if one could find a way to capture GUMs, the energy released when they catalyze baryon "decay" could solve the "energy crisis".

We start by analyzing the "baryon degeneration" problem : could GUMs with $\Delta B \neq 0$ cross-sections as large as those suggested by Rubakov ¹⁰⁾ and Callan ¹¹⁾ have washed out the baryon number of the Universe supposed to have been generated previously ¹²⁾ by GUTs ? We suppose that the early Universe contains

non-relativistic GUMs in a monopole-to-photon ratio (n_m/n_γ) and that their $\Delta B \neq 0$ interactions with conventional fermions f (quarks and leptons) take the "geometric" forms

$$\sigma_{\text{GUMB} \neq 0} = \begin{cases} \frac{1}{v} \frac{\sigma_0}{E_f^2} & (E_f \geq 1 \text{ GeV}) \\ \frac{1}{v} \frac{\sigma_0}{(1 \text{ GeV})^2} & (E_f \leq 1 \text{ GeV}) \end{cases} \quad (1)$$

The interaction rate for $\Delta B \neq 0$ interactions is then

$$\Gamma_{\text{GUMB} \neq 0} = \left(\frac{n_m}{n_\gamma} \right) \langle \sigma_{\text{GUMB} \neq 0} v \rangle (g_f n_\gamma) \quad (2)$$

where g_f is the number of quark and lepton degrees of freedom ($g_f \sim 40$ at $T \sim \text{few GeV}$) which can participate in $\Delta B \neq 0$ interactions : in mass-energy units :

$$n_\gamma = \frac{2\pi^2(3)}{\pi^2} T^3 \approx 0.24 T^3 \quad (3)$$

The $\Delta B \neq 0$ interaction rate given by Eqs. (1) to (3) should be compared with the expansion time-scale of the Universe

$$t = \sqrt{\frac{90}{32\pi^3 g_T}} \frac{m_P}{T^2} \quad (4)$$

where m_P is the Planck mass and g_T is the total number of relativistic degrees of freedom present at the temperature T : $g_T \approx 0(100)$ at $T \approx \text{few GeV}$. Note that in writing Eq. (4) we have assumed that contributions to the Universe's energy density from non-relativistic matter such as the GUMs themselves are negligible. In the case of GUMs this assumption is justified if we accept the upper bounds on the monopole density coming either from Big Bang nucleosynthesis¹⁴⁾ :

$$\left(\frac{n_m}{n_\gamma} \right) \leq O(10^{-19}) \quad (5)$$

or from the present density of the Universe³⁾

$$\left(\frac{n_m}{n_\gamma} \right) \leq O(10^{-25}) \quad (6)$$

since it is unlikely³⁾ that monopole-antimonopole annihilation would have greatly reduced n_m/n_γ since the epoch when $T \sim O(\text{GeV})$.

Combining the interaction rate (2) and the expansion rate (4) we find that

$$t \Gamma_{\text{GUMB} \neq 0} = O(10^{-1}) \frac{g_f}{\sqrt{g_T}} \left(\frac{n_m}{n_\gamma} \right) \sigma_0 m_P x \begin{cases} \left(\frac{1 \text{ GeV}}{T} \right) & (T \gg 1 \text{ GeV}) \\ \left(\frac{T}{1 \text{ GeV}} \right) & (T \leq 1 \text{ GeV}) \end{cases} \quad (7)$$

The $\Delta B \neq 0$ GUM interactions will be out of thermal equilibrium if $t \Gamma_{\text{GUMB} \neq 0} < 1$. This rough-and-ready criterion for the persistence of a baryon-asymmetry is seen from Eq. (7) to give its tightest constraint on the product $\sigma_0 (n_m/n_\gamma)$ when $T \approx 1 \text{ GeV}$:

$$\sigma_0 \left(\frac{n_m}{n_\gamma} \right) \lesssim O(10^{-19}) \quad (8)$$

If we insert into the criterion (8) the known bounds (5) and (6) on the monopole-to-photon ratio we see that there is no "baryon degeneration" catastrophe. Taking the stricter but highly plausible bound (6) from the present mass density we see that baryon degeneration is avoided if

$$\sigma_0 < O(10^{+6}) \quad (9)$$

whereas Rubakov ¹⁰⁾ and Callan ¹¹⁾ might expect $\sigma_0 = O(1)$.

Now what about baryon number violation in the present era ? The rate of baryon "decays" catalyzed by GUM interactions is

$$\Gamma_{\text{GUMB}} = \sigma_{\text{GUMB} \neq 0} F \quad (10)$$

where F is the flux of GUMs. Let us assume that the present lower limit of about 3×10^{30} years on the baryon lifetime also applies to the "decays" catalyzed by GUMs. In this case one must demand

$$\sigma_{\text{GUMB} \neq 0} F < 1 \times 10^{-38} \text{ sec}^{-1} \quad (11)$$

This is a non-trivial constraint on the GUM cross-sections and fluxes. If we take the cross-section (1) at low energies with $\sigma_0 = O(1)$ we find

$$F < 2 \times 10^{-3} \sigma_{\text{GUM}} \text{ m}^{-2} \text{ day}^{-1} \text{ sr}^{-1} \quad (12)$$

While rather higher than the limits established by experiments ⁷⁾ looking for ionizing monopoles [$v_{\text{GUM}} > 0(10^{-3})?$], this limit is orders of magnitude lower than the recent limit ($F < 0.5 \text{ m}^{-2}\text{day}^{-1}\text{sr}^{-1}$) established by Cabrera ⁸⁾ which applies to monopoles of all velocities. Cabrera ⁸⁾ has one candidate event : if it corresponds to a real GUM flux close to his quoted upper limit, the formula (11) suggests that it should catalyze baryon "decays" with an apparent lifetime

$$\tau_B = 0(10^{28} v_{\text{GUM}}) \text{ years ?} \quad (13)$$

Despite all the uncertainties in the $\Delta B \neq 0$ GUM cross-section (1), there seems to be an incompatibility between present experimental limits on the nucleon lifetime and the existence of a GUM flux close to the limit of Cabrera ⁸⁾, as shown in the Figure. If the monopole flux turns out to be close to the other experimental limits in the Figure, and if they are GUMs, then we would expect baryon "decays" to be observed soon (already ? ⁶⁾).

In any case, it would clearly be very interesting to mount a monopole detector and a baryon decay experiment together in coincidence so as to see if a nucleon "decays" whenever a monopole passes by. The $\Delta B \neq 0$ cross-section (1) may be so large that a monopole could trigger a chain of baryon "decays" during its passage through a baryon decay experiment : its mean free path $\approx (4000/\sigma_0) v_{\text{GUM}} \text{ cm}$ which could easily be $< 10 \text{ cm}$! It is therefore desirable that these experiments be designed with a short dead time after each event is recorded, so as to avoid losing any subsequent events in the chain. This would be particularly unfortunate if the $\Delta B \neq 0$ cross-section (1) were so large that the first event in the chain always occurred so close to the edge of the baryon decay detector that it was outside the fiducial volume and therefore not kept as a valid nucleon decay candidate *).

If monopole interactions with matter are so copious, one might wonder whether they would contribute significantly to the rate of energy loss by monopoles passing through matter, and hence alter their penetration power. However, the energy lost by a monopole in each collision is at most $v_{\text{GUM}} \times 0(1) \text{ GeV}$, giving an energy loss rate of at most $\sigma_0 \text{ MeV/cm}$ compared with $dE/dx \approx 2 \text{ MeV/cm}$ for a minimum ionizing particle passing through scintillator material. Therefore, if $\sigma_0 = 0(1)$, a GUM of mass $0(10^{16} \text{ GeV})$ dropping through the Earth's gravitational field ($v_{\text{GUM}} \approx 2 \times 10^{-5}$) would lose at most $0(10^{-5})$ of its kinetic energy due to $\Delta B \neq 0$ interactions while passing through the Earth.

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So far our analysis has been largely independent of the precise form of the $\Delta B \neq 0$ interactions catalyzed by GUMs. Now, however, we become more specific and discuss their likely pattern in the minimal SU(5) GUT ¹³⁾. The SU(5) GUM is the 't Hooft-Polyakov ²⁾ monopole for the following SU(2) subgroup of SU(5) :

$$\underline{I} = \frac{1}{2} \text{diag}(0, 0, \tau, 0) \quad (14)$$

This monopole is surrounded ^{10), 11)} by condensates containing products of $\underline{I} = 0$ Lorentz-invariant pairs of $\underline{I} = \frac{1}{2}$ left-handed fermions $\epsilon_{\alpha\beta} \epsilon^{ij} f_i^\alpha f_j^\beta$ [α, β Lorentz indices ; i, j SU(2) indices] which have characteristic radial extents of $O(m_f^{-1})$. Some of the condensates have the forms of products of $2N_G$ fermion pairs in some permutation. These have a simple dimensional form apart from mass damping factors : ($|\underline{x}|$ is the distance from the monopole)

$$\langle \text{GUM} | \prod_{a=1}^{2N_G} (f_i^\alpha f_j^\beta)_a | \text{GUM} \rangle = O\left(\frac{1}{4\pi^2}\right) \frac{\prod_{a=1}^{2N_G} \exp[-(m_{f_a}^1 + m_{f_a}^2)|\underline{x}|]}{|\underline{x}|^{6N_G}} \quad (15)$$

In addition, there are condensates obtained from (15) by replacing ¹⁰⁾ fermion pairs with chirality-flipping operators of the same internal quantum numbers which were present in the original Lagrangian, such as mass terms or Higgs fields :

$$\epsilon_{\alpha\beta} \epsilon^{ij} f_i^\alpha f_j^\beta \rightarrow m_f \text{ or } \lambda_f H \quad (16)$$

where λ_f is the $H-f^1-f^2$ Yukawa coupling. The available first generation fermion products are ¹⁰⁾ :

$$(\bar{u}^2 u^2 + \bar{u}' u')(\bar{d}^3 d^3 + e^+ e^-) \quad (17a)$$

$$(\bar{u}^2 \bar{d}^3 - u' e^-)(\bar{u}' e^+ - u^2 d^3) \quad (17b)$$

$$(\bar{u}' \bar{d}^3 + u^2 e^-)(\bar{u}^2 e^+ + u' d^3) \quad (17c)$$

where the superscripts are SU(3) colour indices. With N_G generations one can have products of the terms in (17) with their analogues for the heavier generations, giving interactions with $\Delta B = 0, 1, 2, \dots, N_G$. The expression (17a) and its analogues could be replaced by the appropriate product of fermion masses ($m_u m_d$ or $m_u m_e$, likewise $m_c m_s$ or $m_c m_\mu$, $m_t m_b$ or $m_t m_\tau$, etc., for the heavier generations) or by neutral Higgses and the appropriate Yukawa couplings. The

operators (17b) and (17c) and their analogues could only be replaced by super-heavy Higgses and their Yukawa couplings which are not likely to contribute to low-energy phenomenology.

If there are only three generations, the most important condensates for our purpose of $\Delta B \neq 0$ GUM catalysis purposes are likely to be the $\Delta B = 1$ operators

$$\left. \begin{array}{l} (\bar{u}^2 \bar{d}^3 - u^1 e^-)(\bar{u}^1 e^+ - u^2 d^3) \\ \text{or} \\ (\bar{u} \bar{d}^3 + u^2 e^-)(\bar{u}^2 e^+ + u^1 d^3) \end{array} \right\} \times m_c \left\{ \begin{array}{l} m_s \\ \text{or} \\ m_\mu \end{array} \right\} m_t \left\{ \begin{array}{l} m_b \\ \text{or} \\ m_c \end{array} \right\} \quad (18)$$

Condensates with second or third generation fermions and the same number of mass factors will be suppressed by powers of $(m_{\text{light}}/m_{\text{heavy}})$. Condensates with second or third generation masses replaced by fermion pairs in the heavier analogues of (17b) and (17c) would have $\Delta B = 2$ or 3. Hence they could not cause single baryon "decay", but could in principle facilitate nuclear disintegration catalyzed by a monopole. However, this could only occur via grand unified "Cabibbo" mixing¹⁵⁾ of the heavy and light generations, and would also be suppressed by powers of the nucleon radius divided by the nuclear radius, since the monopole light quark condensates presumably have radii comparable with that of a nucleon. As pointed out by Rubakov¹⁰⁾, the only relevant operators containing more fermion fields are likely to be those with m_μ replaced by $(\mu^+ \mu^-)$ in Eq. (18), coming from the second generation analogue of (17a). This would give the distinctive decay modes

$$p, n \rightarrow e^+ (\mu^+ \mu^-) \quad \text{or} \quad p, n \rightarrow e^+ (\mu^+ \mu^-) + \text{pions} \quad (19)$$

with branching ratios which are not obviously negligible. The operators (18) also give us some distinctive features of baryon "decay" catalyzed by GUMs. They give

$$p, n \rightarrow e^+ + \text{pions} \quad (20)$$

with $p, n \rightarrow e^+ + \text{strange particles}$ suppressed by grand unified Cabibbo angles¹⁵⁾. They do not give $p, n \rightarrow \bar{\nu} + X$ because of the location (14) of the monopole in the SU(5) group. They do not give $p, n \rightarrow \mu^+ + X$, which is expected to occur without Cabibbo suppression and hence with branching ratios 0(20)% in conventional GUTs¹⁵⁾, and may even be the dominant decay modes of baryons in supersymmetric GUTs¹⁶⁾. The cross-section for the GUM-catalyzed "decay" (20) is difficult to estimate, but we guess that the mass factors (18) are not likely to cause our fudge factor $\sigma_0(1)$ to be much larger than unity, particularly since the model calculation of Rubakov¹⁰⁾ gives factors of $1/4\pi^2$ in the normalization of the

condensate density (15). However, our previous analysis suggests that the "decays" (19) and (20) should be present close to the present experimental limit ^{5),6)} on the nucleon decay lifetime if the GUM flux is close to the experimental upper limits ⁷⁾.

It is remarkable that large GUM fluxes and large $\Delta B \neq 0$ cross-sections are not incompatible with experiment. It is exciting that they could soon offer us dramatic experimental confirmation of the basic predictions of GUTs. If they do, we wonder whether monopole-catalyzed baryon "decay" could ever be a useful energy source. One's first (tough) problem would be to stop and control the GUM. However, once this was done each of its nuclear interactions would release the $O(1)$ GeV of energy contained in the rest mass of the nucleon, which is usually inaccessible because one cannot change quarks into leptons and radiation except exceedingly slowly via superheavy vector boson exchange. Maybe GUTs and GUMs will be useful as well as fundamental.

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FIGURE CAPTION

A compilation of experimental ^{7),8)} and theoretical ^{3),14)} limits on the flux of monopoles as a function of their velocity v . The baryon decay constraint (dashed line) only applies to GUMs and is somewhat uncertain.

We note that the most recent limits on the monopole flux from the persistence of the galactic magnetic field are not significantly stronger than the limit from the mass density of the Universe. We have omitted them from the figure for reasons of clarity.