Information-preserving black holes still do not preserve baryon number and other effective global quantum numbers *

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It has been claimed recently that the black-hole information-loss paradox has been resolved: the evolution of quantum states in the presence of a black hole is unitary and information preserving. We point out that, contrary to some claims in literature, information-preserving black holes still violate baryon number and any other quantum number which follows from an effective (and thus approximate) or anomalous symmetry.

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The Standard Model Lagrangian possesses several global U(1) symmetries. Each such symmetry has an associated conserved quantum number. Important among these are baryon number B and lepton number L. The baryon number of a particle is B = 1 if it is a baryon, B = −1 if it is an antibaryon. Consequently, quarks carry B = 1/3, and anti-quarks B = −1/3, while all other particles (e.g. leptons, gauge bosons, gravitons etc.) are assigned B = 0. Similarly, the lepton number of every lepton (electrons, muons, tau-particles and their associated neutrinos) is L = 1, while the lepton number of every anti-lepton is −1, and all other particles are assigned lepton number L = 0.

Since protons are the lightest baryons, baryon number conservation would be violated if a proton could decay. Because electrons and neutrinos are the only free fermions lighter than protons (quarks being confined in mesons or baryons), lepton number would also be violated in such decays.

Processes like

\[ p \rightarrow e^+ + \gamma \text{ or } p \rightarrow e^+ + \pi^0 \quad (1) \]

do not violate the conservation laws of energy, electromagnetic charge, linear or angular momentum. However, they do not occur in nature (at least at the energies so far probed) because they violate the conservation of baryon and lepton number. The apparent stability of the proton and the lack of other similar baryon or lepton number violating processes are both consequences and manifestations of the conservation of baryon and lepton numbers.

Despite the important role of B and L conservation in low-energy physics, it is widely believed that these are both violated at higher energy. Within the Standard (SU(2) × U(1)) Model of electroweak interactions, both B and L are anomalous symmetries, conserved by perturbative processes (in the coupling constants α₁ and α₂) but violated by non-perturbative processes such as those mediated by instantons. At temperatures or energies well below the electro-weak symmetry-breaking scale (\(v_{EW} \simeq 250\text{GeV} \)), these non-perturbative processes are suppressed by the extremely small factor \(e^{-8\pi/\alpha} \) (giving, for example, a proton life-time of \(10^{14}\text{yr} \)). Above this scale, B and L violation are expected to be essentially unsuppressed, although B − L remains conserved within the Standard Model.

Similarly, in the context of any grand unified theory (GUT), baryon-number and lepton-number violating processes would be expected to be generic since the quarks and leptons of a given family would be members of the same representation of the GUT gauge group. The GUT gauge bosons would therefore mediate transformations between quarks and leptons, just as SU(2) gauge bosons mediate transformations between up and down type quarks or between charged leptons and their associated neutrinos.

Thus, while neither electroweak instanton mediated processes nor GUT lepto-quark boson mediated processes have yet been observed, B and L violating processes, such as proton decay, are expected to occur at low energies, albeit with extremely low probability. Moreover, there is strong circumstantial evidence for B violation – the overwhelming predominance of baryons over anti-baryons in the universe. Non-conservation of baryon number is one of the three key ingredients in most models of baryogenesis.

We thus see that B and L are approximately, albeit nearly perfectly, conserved in the low-energy effective theory of the Standard Model.

One arena in which global charge violation has been expected to occur is inside black holes. Formation and subsequent evaporation of a black hole may lead to the so-called information loss paradox – an initially pure state can evolve into a mixed state, thus violating quantum coherence. Often in the literature, this information loss

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is connected with non-conservation of baryon number. Black holes can carry local gauge charges, but cannot carry global charges such as B or L. Since information cannot be pulled back once it crosses the horizon, it is usually said that the baryon number of the initial state of a black hole precursor, or of any material thrown into a black hole, is "forgotten" by the black hole. The baryon number of the final state is thus independent of the baryon number of the initial state. Thus, it is said, information loss implies baryon number non-conservation.

A direct consequence of a black hole’s erasure of the baryon number of an initial incoming state, is that particle processes mediated by virtual black holes can be baryon number violating. On short distances (at high energies), fluctuations in the space-time metric are expected to be large. These fluctuations can be described effectively as virtual black holes and exemplify the possibility of quantum gravity mediated baryon number violation. Since they are quantum gravitational, one expects these processes to be suppressed by inverse powers of the energy scale associated with quantum gravity, $M_F$.

The quantum gravity energy scale is normally taken to be $M_F \sim M_{Pl} \sim 10^{18}$ GeV. This is very high compared to any other scale in nature, so the probability for quantum gravitational processes at low energy will be extremely small. The only exception might be processes involving fundamental scalar fields (Higgs, axions, quintessence field, etc.) where one can imagine processes that are not highly suppressed. The other context where such processes can be problematic is models where the quantum gravity energy scale is much lower than $M_{Pl}$, for example brane world models where typically $M_F \sim 1 - 10$ TeV. Proton decay and similar processes, if directly suppressed only by inverse powers of $M_F$, would be catastrophic in these models, and require rather elaborate fixes, such as placing quarks on one brane and leptons on another.

The debate whether black holes preserve information has been recently renewed after Hawking’s claim that the information loss paradox has been resolved in favor of information preservation. (Since there is no scientific publication available yet, we refer to [8].) The basis of the claim is that black hole formation and subsequent evaporation can be thought of as a scattering process. One sends in particles and radiation from infinity and measures what comes out at infinity. One never probes what happens in the intermediate region. On short time scales (shorter than the life-time of the black hole) one might observe events that appear as information loss. On times scales longer than the life-time of the black hole, the black hole evolution must be unitary and the information is preserved. If one observes the initial state (with no black hole, since it has not been formed yet) and the final state (with no black hole, since it has evaporated), then the evolution must be unitary. Non-trivial contributions from the black hole state decay exponentially with time and do not contribute in the limit where one observes the final state at temporal infinity. This gives a unitary mapping from the initial state to the final state.

In literature, one can often find claims that if black holes preserve information, then baryon and lepton number violating processes cannot be mediated by virtual black holes. Arguments of this type have been used, for example, to question the limits on TeV-scale gravity [7]. Contrary to this point of view, we argue that information preserving black holes still violate baryon number. Our conclusion rests on the observation made above that baryon number is only a low-energy effective quantum number even in the absence of quantum gravity. Viewed from an information theoretic perspective, it is important to realize that when a proton decays, through for example lepto-quark boson mediation in a GUT, no information is lost, any more than information is lost when a neutron decays into a proton by emitting an (off-shell) W-boson (which then “decays” into an electron and electron-antineutrino). Similarly, electroweak instanton mediated B-violating processes do not destroy information. They conserve all the exact quantum numbers and conserved quantities of the initial state: energy, momentum, total angular momentum, electric charge, $B - L$, etc.

How do B and L get erased inside a black hole? Inside the horizon, the in-falling matter collapses and is compressed. When it reaches GUT-scale densities, $\rho \sim 10^{27} g/cm^3$, the system almost immediately becomes neutral with respect to baryon charge regardless of its initial value (see [4] and references therein). This depends on the existence of a GUT. However, one expects that far sooner, the density of the collapsing matter will be characteristic of the electroweak scale, $\rho \sim 10^{19} g/cm^3$, and B and L will be erased by “over-the-barrier” non-perturbative electroweak processes. Indeed, any new beyond-the-standard-model physics for which $U(1)_B$ is just a low-energy effective global symmetry will produce the same effect long before the matter reaches the Planck density, $\rho_{Pl} \sim 10^{94} g/cm^3$. Finally, when matter reaches the Planck density, quantum gravity mechanisms become important (e.g. wormholes). These are also capable of erasing any initial baryon number before the infalling matter crosses the singularity.

This mechanism for destruction of baryon charge should be effective for macroscopic black holes, which live for long time. For virtual black holes there is no definite answer without fully understood quantum gravity. However, there are strong indications that the conclusion remains similar. The rate of global charge disappearance inside horizon was calculated in [8] and shown to be exponential. Thus, even a virtual black hole that lives only one Planck time would get rid of at least $e^{-1}$ of the orig-

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1 This in turn can radically modify some of the basic predictions of the model [4].
inal baryon charge. [In \[10\], the timescale for a related
effect — loss of massive vector hair by a black hole —
was analyzed. When applied appropriately, calculations
are in agreement with \[8\].]

According to these arguments, even an information
preserving black hole can erase the baryon number of the
initial state. This is not a paradox since baryon number
is not actually conserved, it is only approximately con-
served at low energy, temperature and density.

We can treat other global charges on equal footing with
baryon charge. In principle, all the charge conservation
laws that follow from the effective global symmetries or
low energy approximative symmetries (like baryon num-
ber \(B\), lepton number \(L\), individual generational lepton
number \(L_i\), charge conjugation \(C\), parity \(P\), the combined
symmetry \(CP\), etc.) can be violated by black holes whose
evolution is unitary (information preserving). Global
charges whose conservation might not be violated in-
clude \(B - L\), since \(U(1)_{B-L}\) is preserved by the Standard
Model and by many possible GUTs, and CPT, because
no self-consistent local field theory accommodates CPT
violation. However, since there is no dynamics that pro-
tects these symmetries, it is possible that they too can
be violated. Finally, charges whose conservation can not
be violated are those that follow from unbroken gauge
symmetries (continuous like \(U(1)_{EM}\) or discrete), and
space-time symmetries (energy, momentum and angular
momentum).

Charges protected by topological reasons (domain wall
kink number, string and monopole winding numbers,
\(etc.\)) deserve special attention.

Point-like defects like magnetic monopoles can be swal-
lowed by a black hole. Since magnetic monopoles are
charged with magnetic gauge charge, a black hole can-
not violate a net monopole number conservation. If a
monopole-antimonopole pair is swallowed by a black hole,
it can annihilate (unwind) inside \[11\] without violating a
net topological charge. If a number of monopoles of the
same magnetic charge is swallowed, the black hole be-
comes magnetically charged and cannot evaporate com-
pletely. Consider a black hole that captures \(N \gg 1\)
monopoles. A monopole is a highly coherent state of
many gauge quanta and emission of a monopole by a
black hole is highly suppressed. Even if this process is
somehow allowed, the Hawking temperature of a black
hole becomes of order of a monopole mass only at the
end of evaporation, and a black hole could radiate only a
few monopoles. Generically, since the Hawking radiation
can not violate the gauge symmetry, a black hole can not
evaporate completely. Instead it leaves a remnant — an
extreme magnetically charged Reissner-Nordstrom black
hole. The mass of the (non-rotating) remnant \(M_r\) must
be greater than the magnetic charge \(Q_m\) of the black
holes, \(M_r \geq Q_m\), or otherwise the remnant would be a
naked singularity. The Hawking temperature of an ex-
tremal black hole is zero and such a black hole does not
evaporate further. Thus, the net topological charge re-
ains conserved.

The situation with extended defects is more compli-
cated. It was shown in \[12\] that there is a non-vanishing
energy and angular momentum flux through the black-
hole horizon in non-stationary black hole-string and black
hole-domain wall configurations. This implies that, in
principle, a black hole can accrete energy from an ex-
tended topological defect. In the case of a finite size
defect, i.e., a cosmic string ending on monopoles or a do-
main wall bounded by a string, the final configuration
would be a black hole with a defect swallowed within a
horizon. If the defect did not carry any gauge charges,
such a black hole could evaporate completely. In this
process, the total topological charge would not be vio-
lated since finite size defects (cosmic strings ending on
monopoles or domain walls bounded by strings) have a
trivial net topology. Infinite strings and domain walls are
configurations with a non-trivial topology. However, they
can not be completely swallowed by a black hole since the
part of the defect that is accreted within a horizon gets
replaced with a part pulled out from infinity.

The other question related to the previous discussion
is nucleation of black holes within a defect. It is well
known that a cosmic string can break if a monopole-
antimonopole pair is nucleated on the string. In a similar
way a cosmic string can break if a pair of black holes is
nucleated on it. The analog process in a domain wall case
would be a black string loop (a one dimensional general-
ization of a black hole solution) nucleating on a domain
wall world sheet \[13\]. A finite defect would be broken
into a finite number of pieces by these processes. How-
ever, a finite defect has a trivial net topology. An infinite
defect with non-trivial topology can never be broken into
a finite number of pieces in finite time. We thus conclude
that true topological charges can not be broken by pro-
cesses induced by black holes. We note, though, that in
practice we often meet objects that do not meet the strict
criteria of a truly topological configuration. For example
cosmic strings and domain walls that could arise in phase
transitions in early universe, though possibly larger than a
horizon size, are still finite objects.

To summarize, a black hole whose evolution preserves
information in the strict sense makes distinction between
different types of quantum numbers:
1. quantum numbers that are violated:
   \(\text{eg. } B, L, L_i, C, \text{ and } CP\);  
2. quantum numbers that \textit{might} not be violated:
   \(\text{eg. } B - L, \text{ and } CPT\);

\footnote{Note that there is no known solution of such a configuration. A simple real scalar field with broken \(Z_2\) symmetry does not allow for such solutions but some more complicated models may in
principle.}
quantum numbers that are not violated within the currently understood theory: 
*eg. Q_{EM}, E, \vec{L}, \vec{p},* and true topological charges.

This distinction is in agreement with an argument given by Hawking in [3]. There, probability amplitudes for processes mediated by virtual black holes were derived using Euclidian path integral formalism. After averaging over all diffeomorphisms (all metrics that contribute to a particular process), the formalism gives a zero transition amplitude unless energy is conserved. After averaging over all the gauge degrees of freedom, the formalism gives a zero transition amplitude unless the gauge charges are conserved. Since one does not average over global symmetries, a transition amplitude can be non-zero even if global charges are not conserved. The conclusion that is drawn in [3] is that processes where quantum coherence is lost may lead to non-conservation of global charges. The point we are making in this paper is that even black holes whose evolution preserves the information do not conserve certain global charges, such as baryon and lepton number. This is not in contradiction with conclusions in [3], since baryon number non-conservation does not imply information loss.

Arguably, the most important consequence of this statement is that virtual black holes can mediate proton decay in models with low energy scale quantum gravity. Specifically, the claim that black holes preserve information does not prevent proton decay of this type. There may be other ways to protect the proton like gauging the baryon number [13]; however, to the extent that these are successful, it seems that they must suppress baryon-number violation at all energy scales below the quantum gravity scale, and hence at all times in the history of the universe. In order for them to be compatible with generic models of baryogensis [2], some modifications that allow for baryon number violation in the early universe are necessary.

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Note added: After the completion of this work, a long awaited paper by S. Hawking appeared on the web [16]. At the end of the paper, the author also addresses the question of baryon number violation by information preserving black holes. The author’s conclusion differs from the one presented here. We leave the judgment to the reader.

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