Limits on Nonconservation of Baryon Number

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(Received 31 July 1979)

Existing data from deep underground experiments are analyzed to deduce the *total* lifetime of the nucleon to be $\gtrsim 10^{30}$ yr (at 90% confidence level) considering decay modes given by currently popular grand unified theories. Limits on partial rates of some of the important decay modes are also given.

A striking prediction of grand unified gauge theories of weak, electromagnetic, and strong interactions is that the nucleon is unstable to baryon-number–nonconserving interactions.[1] Recently, the experimental confirmation of the predictions of the Weinberg-Salam gauge theory[2] of electroweak interactions, coupled with the realization that the instability of the proton could lead to an explanation of the observed baryon asymmetry in the universe[3] has led to a heightened interest in the question of conservation of baryon number. In some versions of the Pati-Salam models, based on SU(4),[4] the nucleon lifetime τ_N is estimated to range from 10^{29} to 10^{34} yr.[4] In the Georgi-Glashow model,[5] based on SU(5), theoretical calculations now indicate that τ_N may be as low as 10^{31} yr with a "conservative" upper bound of 3×10^{32} yr.[6,7] The limit of 10^{32} yr corresponding to tens of decays per year in several thousand tons of matter is accessible to experiment and, in fact, "dedicated" experiments are now being seriously proposed for an exciting confrontation with theory. These developments have led us to analyze existing data which yield the most restrictive limits.[8-10] These data were obtained from deep underground experiments performed by a group from the Case Western Reserve University, the University of the Witswatersrand, Johannesburg, and the University of California, Irvine (CWI).[11]

The experiment consisted of measuring the signals seen with a large array of liquid scintillation detectors and flash tubes operated deep underground ($\sim 9\times10^5$ g/cm^2 standard rock) for several years. The primary motivation was to study the intensity and angular distribution of cosmic-ray muons from neutrino produced in Earth's atmosphere. Based on the product of detector tonnage and run time (67 ton yr) and the observed six pairs of pulses identified as muons which stopped and decayed in the detector, Crouch and Reines reported[12] that the partial lifetime[13] for proton *or* neutron decay modes which result in muons as $>2\times10^{30}$ yr. An updated reanalysis led to a modified upper bound[9]

$$\tau_n{}^{\mu},\tau_p{}^{\mu} > 3\times10^{30}\ \text{yr} \tag{1}$$

(superscript μ is to indicate that this is a partial lifetime[13]) or for isosymmetric nuclear matter

$$\tau_N{}^{\mu} > 6\times10^{30}\ \text{yr}. \tag{2}$$

Positive pions associated with ν or e decay modes of nucleons could give rise to the muons observed in the apparatus and such events were included in the quoted rate because no separation of "prompt" $\mu^\pm$ from π^+ decay to μ^+ was possible. In general, in theories [e.g., SU(5)] with $e \leftrightarrow d$, $\mu \leftrightarrow s$ (lepton-quark) symmetry the dominant baryon-number–nonconserving decays are into electrons rather than "prompt"-muon final states. In the context of SU(5), the decays $N\to$ (prompt)$\mu + X$, where X are nonstrange meson(s) are Cabibbo suppressed, whereas $N\to$(prompt)$\mu + K$ or (prompt)$\mu + K + \pi$ decays are relatively suppressed by phase space. In that theory the inclusive branching ratios are estimated to be as follows[14] (μ here again means prompt μ):

$$\begin{aligned} &p\to e^+ + X \sim 80\%, \quad n\to e^+ + X\sim 80\%;\\ &p\to \bar\nu_e + X\sim 15\%, \quad n\to\bar\nu_e + X\sim 20\%;\\ &p\to\mu^+ + X\sim 5\%, \quad n\to\mu^+ + X\sim \text{a few percent};\\ &p\to\bar\nu_\mu + X\sim \text{very small}, \quad n\to\bar\nu_\mu + X\sim\text{very small}. \end{aligned} \tag{3}$$

The actual rates for exclusive modes involving various meson channels are controlled by the detailed dynamics of how the quark-antiquark system evolves into those channels in the final state. We estimate the probability of decays resulting in π^+ from $p\to e^+ + X$ to vary from $\frac{1}{5}$ to $\frac{1}{2}$. The probability of π^+ resulting from $p\to\bar\nu_e + X$ is close to 100%. For $n\to e^+ + X$ the fraction of π^+ is very small (≈ 0) and for $n\to\bar\nu_e + X$ it ranges again from $\frac{1}{5}$ to $\frac{1}{2}$. Using (3) and these estimates we have[15] for proton decay, $35\% \lesssim P_{\pi^+}{}^{p} \lesssim 65\%$; for neutron decay, $5\% \lesssim P_{\pi^+}{}^{n} \lesssim 15\%$, where P_{π^+} is the probability of decays leading to π^+. Taking (4) into consideration we deduce a branching ratio of about 15% for nucleon decays resulting in μ stops in isosymmetric nuclear matter[16] and using (2) we conclude that for SU(5) the nucleon *total* lifetime is

$$\tau_N \gtrsim 10^{30}\ \text{yr}. \quad (4)$$

For Pati-Salam theories the dominant nucleon decays are into neutrinos and mesons.[4] For p decays the final state will therefore always contain a π^+ yielding $P_{\pi^+}{}^p \approx 100\%$. For neutron decays $P_{\pi^+}{}^n$ is estimated to be $\gtrsim 20\%$. We are thus led to deduce a branching ratio of about 30% for μ stops[16] in isosymmetric nuclear matter and so for Pati-Salam theories the experimental limit (2) based on μ stops leads to

$$\tau_N \gtrsim 2\times 10^{30}\ \text{yr}. \quad (5)$$

In addition to μ stops, the throughgoing particles (presumably muons) from the same CWI experiment[11] also lead to limits on several decay modes. Altogether 600 single counts were recorded which could be due to throughgoing electrons, photons, mesons, or muons. The observed signal was consistent with that predicted from two conventional sources: atmospheric muons (peaked in the vertical direction) and those resulting from ν_μ interactions (comparatively isotropic) in the surrounding rock. To deduce a limit on nucleon lifetime we assert that at 90% confidence level one can attribute less than 150 counts to nucleon decays.

We first consider two distinctive modes: $p \to e^+ + \pi^0$ and $n \to e^+ + \pi^-$. The sample of nucleons involved is that within one effective range R which we take to be about 100 g/cm^2. The lifetime limit of these modes obtainable from the observed counts is given by

$$\tau_N/B \gtrsim (67\ \text{ton yr})(R/d)(f/150) \times 6\times 10^{29}/\text{ton}, \quad (6)$$

where B is the relevant branching ratio, d (~11 g/cm^2) is the thickness of the slab detector, and f is a correction factor determined by geometrical acceptance, detector efficiency, and the number of particles responsible for a signal from the mode under consideration. For the stated modes we estimate that $f \gtrsim \frac{1}{4}$ yielding a limit on their partial lifetime given by

$$\tau_N/B \gtrsim 6\times 10^{29}\ \text{yr}. \quad (7)$$

For three-body modes such as $p \to e^+ + \pi^- + \pi^+$, $n \to e^+ + \pi^- + \pi^0$, etc., the limits from these data would lie roughly in the same range. For modes involving muons ($R \approx 200$ g/cm^2) such as $\mu + K$, $\mu + \pi$, etc., we have

$$\tau_N/B \gtrsim 2\times 10^{30}\ \text{yr}. \quad (8)$$

All these modes are expected to be relevant to SU(5).

To deduce a limit on the total lifetime (τ_N) from Eq. (7) we need to determine B. For this purpose consider decay modes with e^+:

(a) $p \to e^+ + \pi^0$, $\quad n \to e^+ + \pi^-$;

(b) $p \to e^+ + \rho^0$ $(\rho^0 \to \pi^+ + \pi^-)$,

$\qquad n \to e^+ + \rho^-$ $(\rho^- \to \pi^- + \pi^0)$;

(c) $p \to e^+ + \pi^+ + \pi^-$ $(p \to e^+ + \pi^0 + \pi^0)$,

$\qquad n \to e^+ + \pi^- + \pi^0$.

Notice that without $p \to e^+ + \pi^0 + \pi^0$ either the proton *or* the neutron decays in (a), (b), and (c) lead to an e and a π^0. Therefore, for isosymmetric nuclear matter the fraction of $N \to e^+ + X$ events with π^0 in the final state is $\gtrsim \frac{1}{2}$ so that [with use of (3)] the branching ratio for $N \to e^+ + \pi^0 + X$, with X being zero or one pion, is $\gtrsim 40\%$ leading to another limit [for SU(5)][17]

$$\tau_N \gtrsim 2\times 10^{29}\ \text{yr}. \quad (9)$$

For Pati-Salam models[4] the dominant decays involve 3ν so that the accompanying mesons carry much less energy leading to somewhat smaller numbers for modes such as $3\nu + \pi + X$:

$$\tau_N/B \gtrsim 10^{29}\ \text{yr}. \quad (10)$$

It is perhaps useful to cite another limit deduced from a separate, albeit somewhat less sensitive, experiment (Sobel *et al.*[18]), also performed by the CWI group deep underground in a South African mine.[19]

The apparatus was originally designed for detection of solar neutrinos by elastic scattering of electrons. The detector was a liquid scintillator weighing about 4 ton with a run time of $\frac{1}{18}$ yr. An exponentially falling energy spectrum (~ $3e^{-E/1.45}$) was observed extending up to 20 MeV. The spectrum of photons from π^0 decays (resulting from nucleon decay modes such as $p \to e^+ + \pi^0$, $n \to \nu + \pi^0$, etc.) in flight is flat extending from about 10 MeV to about 490 MeV. Using only the interval 20 to 490 MeV we can set an upper limit on nucleon decays for each of the modes such as $N \to e + \pi^0 + X$, $e + X$:

$$\tau_N/B \gtrsim 2\times 10^{29}\ \text{yr}. \quad (11)$$

TABLE I. Limits on baryon-number—nonconserving decays. Numbers here are for nucleon decays in isosymetric nuclear matter. The branching ratios are for the SU(5) model of Georgi and Glashow. For the Pati-Salam model we have used a 30% branching ratio into μ stops. See text.

Technique	Mode	90%-confidence-level limit on partial rate (yr)	Assumed branching ratio	90%-confidence level limit on total lifetime (yr)
μ stops in detector (Refs. 9, 11, and 12)	μ stops	6×10^{30}	$\approx 15\%$	10^{30}
Throughgoing particles (Ref. 11)	$e+\pi^0+X$	6×10^{29}	40%	2×10^{29}
	$e+X$	6×10^{29}	80%	5×10^{29}
	$\mu+K$, $\mu+\pi$	2×10^{30}		
	$3\nu+\pi+X$	10^{29}		
γ rays from surrounding rock (Refs. 10 and 18)	$e+\pi^0+X$, $e+X$	2×10^{29}		
ν_μ from baryon decays in Earth (Refs. 10, 11, and 19)	$\nu_\mu+X$ ($X=\pi,\rho,K$,etc.)	2×10^{26}		
	$3\nu_\mu$	5×10^{26}		
Summary	All			$>10^{30}$ (Georgi-Glashow) $>2\times10^{30}$ (Pati-Salam)

For limits on nucleon decays up to a few times 10^{29} yr neutrino backgrounds are unimportant and such limits can be obtained "incidentally" with a modest experiment like that of Sobel *et al.*[18] However, an experiment which aims to go beyond the CWI limit of 10^{30} yr must discriminate effectively against neutrino backgrounds. To accomplish this one needs to be able to study the detailed energy and angular characteristics of the events, a requirement not met by the above detectors. This information can be best obtained by a detector that is capable of containing the entire baryon decay.

In conclusion, the limits on various modes deduced from the existing data obtained from deep underground experiments are shown in Table I and for both the Georgi-Glashow and the Pati-Salam models the limit on the total lifetime of the nucleon to baryon number nonconserving decays is

$$\tau_N \gtrsim 10^{30}\ \text{yr}. \qquad (12)$$

The limit (12) can be compared with Goldman and Ross's theoretical prediction of 1.3×10^{31} yr and their upper bound of 3×10^{32} yr.[6] *Using their calculation* we estimate that the mass of the X and Y bosons (assuming, as usual, $M_X=M_Y$) of SU(5) is $\gtrsim 2.4\times10^{14}$ GeV.

We would like to thank Dr. H. W. Sobel and Dr. J. Schultz for discussions.

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[12]Reines and Crouch, Ref. 8.

[13]By partial lifetime into a specific decay mode we mean total lifetime divided by the branching ratio into that mode.

[14]These numbers are the result of general consensus of some of the theoretical calculations of Ref. 7, T. J. Goldman (private communication), and our own estimates.

[15]These are obtained by one of us (A. S.) by a reasonable variation of the proportions of X into a spinless meson, a vector meson, or two spinless mesons.

[16]By using the measured absorption cross sections of π^+ on nuclei we estimate that about $\frac{1}{2}$ of the π^+ would result into μ^+.

[17]Final states with η, as opposed to π^0 in (a)–(c), are likely to be suppressed relative to π^0's. Since η and ω have substantial branching ratios for decays to π^0 their inclusion will enhance the inequality $(N\rightarrow e^+ +\pi^0 +X)/(N\rightarrow e^+ +X) \gtrsim \frac{1}{2}$ and the resulting limit (9).

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[19]An amusing limit on nucleon decays of the form $N \rightarrow \nu_\mu + X$, $N\rightarrow 3\nu_\mu$ can be obtained at the level of (2–5) $\times 10^{26}$ yr by attributing the entire observed ν_μ flux to decays of all the baryons in the earth. For details see Ref. 10.

Experimental Test of One-Pion Exchange and Partial Conservation of Axial-Vector Current in Proton-Nucleus Charge-Exchange Reactions at 144 MeV

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We have measured the differential cross sections of the (p,n) reaction on ^{6}Li, ^{12}C, and ^{14}N to the ground state of the final nucleus ($\Delta J=1$, $\Delta I=1$, $\Delta P=0$) at $E_p=144$ MeV and $0° < \theta_{\rm lab} < 20°$. We treat the nuclei as elementary particles, extract the initial-nucleus–pion–final-nucleus coupling constants, and compare them with predictions based on the partial conservation of axial-vector current hypothesis. The calculations, which have no free parameters, agree with the data for ^{6}Li and ^{12}C, but not for ^{14}N.

A common feature of the three reactions, $p + {}^6\text{Li} \rightarrow n + {}^6\text{Be}$, $p + {}^{12}\text{C} \rightarrow n + {}^{12}\text{N}$, and $p + {}^{14}\text{N} \rightarrow n + {}^{14}\text{O}$ is that the change in nuclear angular momentum (J), isospin (I), and parity (P) is the same; namely, $\Delta J = 1$, $\Delta I = 1$, and $\Delta P = 0$. These nuclei undergo the same change in their quantum numbers in the (p,n) reaction as in an allowed Gamow-Teller β decay, which is also the quantum-number change required of a one-pion exchange mechanism. We therefore *conjectured* that the reactions are dominated by *one-pion* exchange for small momentum transfer ($q^2 \lesssim m_\pi^2$) and intermediate-energy protons ($E_p = 144$ MeV).

The experiment was carried out at the Indiana

