BNL-23585

MASTER

CONF-7710107--2

TALK GIVEN AT THE BEN LEE MEMORIAL INTERNATIONAL CONFERENCE ON:
PARITY NONCONSERVATION, WEAK NEUTRAL CURRENTS AND GAUGE THEORIES

At the Fermi National Accelerator Laboratory
October 20-22, 1977

STATUS OF CONSERVED QUANTUM NUMBERS

Maurice Goldhaber
Brookhaven National Laboratory*
Upton, New York 11973

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

*Under the auspices of the U.S. Department of Energy.

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

MN ONLY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

BNL-23585

STATUS OF CONSERVED QUANTUM NUMBERS

Maurice Goldhaber
Brookhaven National Laboratory*
Upton, New York 11973

The phrase "conserved quantum numbers" has a rather definitive ring to it; it might be more cautious to talk of them as quantum numbers for which nonconservation has not been established.

Though the limits of quantitative measurements have been considerably extended in recent years, the status of these quantum numbers has not changed qualitativel . There is much activity, especially concerning the laws of conservation of baryons and of muon number, as if change were just around the corner.

If we look at the historical development of the conservation laws, we find one or more of the following conditions fulfilled:

1. No breakdown has been reported for the property being considered. (Early generalizations from somewhat qualitative evidence.)
2. A breakdown has been explicitly searched for and not found. (This usually leads to a quantitative limit.)
3. A particular conservation law is a consequence of a successful, general theory which explains many phenomena that appear at first sight to be unrelated (though the conservation law also may have been originally assumed in formulating the theory), the foremost example being conservation of electric charge.

---

*Under the auspices of the U.S. Department of Energy.

Two kinds of conservation law exist:

A. Restricted conservation law: A quantity is conserved with respect to some but not all interactions (e.g., strangeness, which is conserved in strong and electromagnetic, but not in weak, interactions).

B. Absolute conservation law: This is believed to hold with respect to all known interactions because of a fundamental symmetry, (e.g., conservation of electric charge follows from gauge invariance). An absolute conservation law cannot be proved empirically. This would require measuring quantities that are either zero or infinite, values which can be approached by successive improvements in experimentation but not reached. An absolute conservation law is therefore a theoretical statement.

From an operational point of view, a conservation law being absolute means that no known interaction leads to its breakdown; e.g., experimental limits on conservation of electric charge (discussed below) are good enough to conclude that if this conservation law were to break down it would be with an effective strength weaker than that of any of the known interactions. We should remember that from an empirical point of view such a possibility cannot be excluded.

The conservation laws that have withstood empirical tests are shown in Table I. Although the first three laws suffice to describe the empirical evidence, theoreticians like to hold on to the older fourth law, lepton number conservation, as a general framework for the discussion of a number of potential reactions, such as $\mu^- \to e^- + \nu$.

TABLE I

CONSERVED QUANTUM NUMBERS

1) Q (ELECTRIC CHARGE)

2) B (BARYON NUMBER)

3) L_X (X = e, μ, (τ) ; SPECIFIC LEPTON NUMBER).

4) L (LEPTON NUMBER)

It may be useful to look back at the history of the oldest conservation law, which is still being hotly debated today, that of baryons, because this history provides some general lessons for other conservation laws. However, I shall not make an attempt at completeness here.

In an essay written in honor of Dirac for his 70th birthday, Pais[1] wrote (p. 86): "Much speculation arose at that time to the effect that the negative energy states might be associated with the proton. For this and for another reason, a comment by Weyl [Z. Physik 56, 330 (1929)] is of interest: 'It is plausible to anticipate that, of the two pairs of components of the Dirac quantity, one belongs to the electron, the other to the proton. Further, two conservation laws of electricity will have to appear, which state (after quantization) that the number of electrons as well as of protons remain constant. To these conservation laws must correspond a twofold gauge invariance, involving two arbitrary functions.' Here then is the earliest version of the conservation law of baryons, involving all baryons known in 1929."

Weyl's genius led him to guess something important. But had he set himself the task of stating how the proton might decay (conserving electric charge), he would not at that time have known any particles it could decay into.

It did not take long for Weyl and others to realize that Dirac's positive particle could not be the proton. The conservation law for nucleons was explicitly postulated ten years later by Stueckelberg[2] as a conservation law of a different kind from that of electricity.

He said (p. 317): "Besides the conservation law of electric charge, which follows from Maxwell's theory, there clearly (offenbar) exists a further conservation law: For all observed transformations of matter, no trans-

formations of heavy particles (neutron and proton) into light particles (electron and neutrino) have yet been observed. We therefore wish to postulate a conservation law of the heavy charge (schwere Ladung)."

Ten years later Wigner[3] rediscovered the conservation law of nucleons, saying (p. 525, footnote): "It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino."

Why did these three learned gentlemen, Weyl, Stueckelberg, and Wigner, feel so sure that baryons are conserved? Well, you might say that it's very simple; they felt it in their bones. Had their bones been irradiated by the decays of nucleons, they would have noticed effects considerably exceeding "permissible radiological limits" if the nucleon lifetime were $<10^{16}$ years and if at least 10% of the nucleon rest mass were to appear as radiation absorbable in the body. That is a fairly sensitive measurement, but one can do much better by a deliberate experiment.

A quarter century after Weyl's conjecture the first attempts were made to test the assumption of nucleon stability explicitly[4]. From simple considerations and by simple experiments we could conclude

a) $\tau_N > 10^{20}$ years, no matter how the nucleon disappears,

b) $\tau_{p_f} > 10^{21}$ years and $\tau_{N_b} > 10^{22}$ years,

if ionizing particles $\gtrsim$ 100 MeV are emitted in the decay of free protons (p_f) or bound nucleons (N_b). I shall return to details shortly.

Summing up, we said (p. 1158): "We cannot conceive of an experiment which would prove the absolute stability of nucleons, but judging from the demonstrated 'practical' stability of nucleons we conclude that the law of conservation of nucleons can be used with considerable confidence in discussions of 'practically observable' nuclear reactions. It proves very useful, for example, for hyperon reactions where it permits the conclusion that particles observed to decay into nucleons must be made from pre-existing nucleons or be produced in pairs (particles plus antiparticles). It also follows that nucleons must be found among the ultimate decay products of such hyperons; otherwise the decay of nucleons via virtual hyperon states would be observable. If nucleon pair production processes should be observed, the number of nucleons would only be conserved in an algebraic sense."

Pais[5)] suggested the collective name "baryon" for nucleons and "heavy" V particles. Since then one speaks of a conservation law of baryons. But of course, for practical purposes, tests of this law are confined to nucleons: free or bound protons, and bound neutrons.

During the next decade the spirit of testing conservation laws led to remarkable successes: observation of the breakdown of the symmetries P, C, and T.

To give some perspective on the lifetime limits with which we are dealing when we discuss nucleon decay, Table II shows some "long times" that play an important role in physics, geophysics, and astrophysics.

Unlike Weyl, who couldn't have said in 1929 how the proton might decay, we are now confronted by a multiplicity of possibilities. Figure 1 shows schematically all the particles which are lighter than a nucleon in mass and into which a nucleon might conceivably decay. If one counts particles and antiparticles as well as members of multiplets separately, one comes up with

TABLE II

SOME "LONG TIMES"

$T_{1/2}$ OF ^{238}U	:	4.5×10^{9} YR
AGE OF EARTH	:	4.6×10^{9} YR
TIME SINCE "BIG BANG"	:	$\sim 1.5 \times 10^{10}$ YR
$T_{1/2}$(SPONT.FISS.) OF ^{238}U	:	10^{16} YR
$T_{1/2}$($\beta\beta$) OF ^{130}Te	:	1.4×10^{21} YR

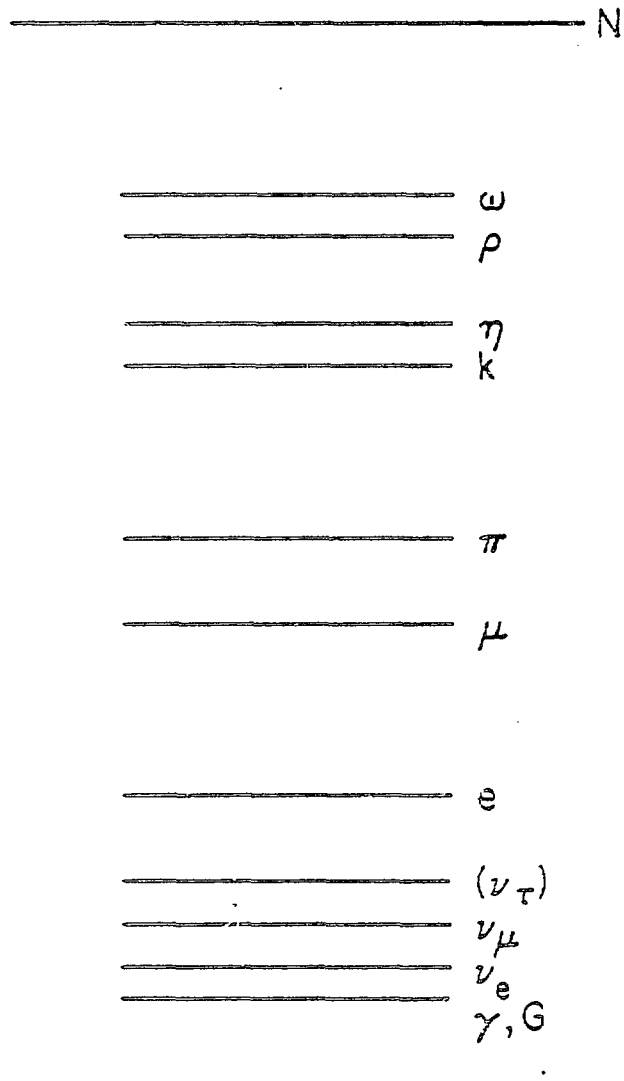

FIG. 1

Schematic of particles of mass lower than that of a nucleon.

some 20-odd known particles into which a nucleon could decay. Because of the many possibilities confronting an experimenter, I should like to urge those who are formulating theories of nucleon decay to try to predict, as far as possible, specific decay modes and specific branching ratios, because for each specific decay mode one can design a deliberate experiment — we could call it a dedicated experiment — not just take a free ride on various and sundry neutrino experiments. As an example, if there were a decay mode $p \to \pi^+ + \nu$, the π^+ would have a well-defined energy, equivalent to nearly half the proton mass, and a characteristic decay chain $\pi^+ \to \mu^+ \to e^+$. We might thus be able to see a π peak on top of the continuum induced by atmospheric neutrinos, and in principle this would allow us to measure very long lifetimes. Roughly, one can say that for measuring a lifetime of the order of 10^{31} years (which is a little beyond the limit given by Reines for a specific decay mode leading to μ^- emission) one needs about 100 tons of matter to get of the order of 10 events per year, and proportionately more for longer times. Just to obtain a measurable signal one needs very large quantities of matter, and therefore it is natural to combine nucleon decay searches with neutrino searches, but by emphasizing as well as we can the detection of specific modes, we can probably push the search for certain partial decay modes to much longer times than would be otherwise poss[illegible].

Table III updates a 1958 paper with Gary Feinberg[6]. Here th[illegible] bol $\odot$ means "empirically equal" (see ref. 7). Again, let us remember that a measurement cannot yield an exact value zero, but the atomic beam measurements yield charge differences, shown in Table III, which are compatible with zero (see Table IV). If one makes the assumption that the neutron has charge zero, one can obtain better limits from experiments on bulk matter[8] (where different proton-neutron ratios, e.g., different isotopes, have so far not

TABLE III

G. FEINBERG AND M.G., PROC. NAT. ACAD. SCI., 45, 1301 (1958)
(UPDATED)

THE CHARGES OF THE KNOWN PARTICLES INTO WHICH A NUCLEON MIGHT DECAY ARE

$$Q_x = 0, \pm 1\, Q_e.$$

ELECTRIC CHARGES OF KNOWN PARTICLES CAN BE EXPRESSED IN TERMS OF A FEW INDEPENDENT CHARGES WHICH WE CAN CHOOSE TO BE

$$Q_e,\ Q_p,\ Q_n,\ Q_\mu \text{ (AND } Q_\tau\text{)},$$

OR WE CAN CHOOSE THE DIFFERENCES FROM UNIT CHARGE

$$\delta q_p,\ Q_n,\ \delta q_\mu\ (\delta q_\tau).$$

TABLE IV

L. J. FRASER, E. R. CARLSON AND V. W. HUGHES (1968)

(See ref. 7)

$$Q({}^{39}_{19}K_{20}) = 19\delta q_p + 20Q_n$$
$$= (0.84 \pm 0.78) \times 10^{-18} Q_e;$$

$$Q({}^{133}_{55}Cs_{78}) = 55\delta q_p + 78Q_n$$
$$= (1.62 \pm 0.70) \times 10^{-18} Q_e;$$

IT FOLLOWS THAT

$$\delta q_p = (0.9 \pm 2.0) \times 10^{-19} Q_e;$$
$$Q_n = (0.4 \pm 1.5) \times 10^{-19} Q_e.$$

FROM $n \rightarrow p + e^- + \bar{\nu}_e$ IT FOLLOWS THAT

$$Q_{\bar{\nu}_e} = -(0.5 \pm 3) \times 10^{-19} Q_e.$$

been used in the same setup).

If the charge differences were not exactly equal to zero, nucleon stability would trivially follow from charge conservation. But let us assume that the charge differences are exactly equal to zero (a widespread conjecture or tacit assumption, which would follow from Dirac's quantization condition if magnetic monopoles exist). Nucleons might then decay to some of the particles shown in Fig. 1. As mentioned above, there are two essentially different methods[4)] for measuring nucleon decay:

1. Detection of disappearance of a nucleon from a nucleus.
2. Detection of radiations emitted in the decay of a nucleon.

The first, the nuclear method, of which there are now two varieties, gives the results shown in Table V. These methods are fairly insensitive to the particular decay mode: If a nucleon disintegrates, or even "disappears without a trace" (when there was talk of "continuous creation" one might also have had to contemplate "continuous disappearance" of nucleons), it leaves a hole in the nuclear shell, which in ^{232}Th is, for most of its nucleons, equivalent to raising the energy above the fission threshold. From a limit on the spontaneous fission lifetime of ^{232}Th, one can deduce a limit on nucleon lifetime which is ~200 times as large. This method would also be valid if processes involving two or more nucleons played a role in the "disappearance" of nucleons.

The radiochemical variation of the nuclear method relies on the detection of a specific final nucleus resulting from the original one.

The nuclear methods give limits on total lifetimes for nucleons, whereas the counting methods give limits on partial lifetimes. Both methods ultimately suffer from neutrino-induced background due to charged or neutral currents. Perhaps such experiments will ultimately be carried out on the

TABLE V

NUCLEAR METHODS

1) SEARCH FOR FISSION INDUCED IN ^{232}Th (1954).
FLEROV ET AL (1958)[a)]

$$T_N > 2 \times 10^{23} \text{ YR}$$

2) RADIOCHEMICAL METHODS.
GENERAL SUGGESTION BY P. ROSEN (1975)[b)]

SPECIFIC EXAMPLES INVESTIGATED:

I. J. C. EVANS AND R. I. STEINBERG (1977)[c)]

$$^{130}Te \longrightarrow {}^{129}Xe \qquad T_N > 1.6 \times 10^{25} \text{ YR}$$

II. FIREMAN ET AL (1977)[d)]
STEINBERG ET AL (1977)[e)]

$$^{39}K \longrightarrow {}^{37}Ar \qquad T_N > 2.2 \times 10^{26} \text{ YR}$$

a) See ref. 7.

b) Phys. Rev. Lett. 34, 774 (1975).

c) Science 197, 989 (1977).

d,e) Reported at International Conference on Neutrino Physics, Elbrus, USSR, June 1977.

moon to escape the effects of atmospheric neutrinos.

I have discussed the question of the history and of the empirical evidence concerning baryon conservation at such length because there has been no recent systematic review of this subject.

Theory teases the experimenters to bigger efforts. Within the general framework of unified gauge theories, the possibility of transitions from quarks to leptons has been discussed. Pati and Salam[9] consider a nucleon to be made of three quarks of integer charge to which they assign a corresponding flavor. Other theories[10] make use of the more "conventional" fractionally charged quarks. . . each case the nucleon lifetime cannot be estimated without further assumptions on properties of heavy intermediate "lepto-quark" gauge bosons. However, it has also been demonstrated that in some unified gauge theories the proton can be absolutely stable[11]. The theoretical situation has been reviewed by Gell-Mann, Ramond and Slansky[12].

For conservation of electric charge the most sensitive tests are probably those that search for decay of an electron into neutral particles, e.g., $e \rightarrow 3\nu$ (detected by x-rays which would follow disappearance of a K-electron) or $e \rightarrow \nu + \gamma$. Some of the data are summarized in Table VI (see, e.g., ref. 7). The lifetime limits are good enough to indicate that none of the known interactions break charge conservation[6], as mentioned above.

The search for $\mu \rightarrow e + \gamma$, which became a hot subject about two years ago, still continues. The present situation is still the same as that recently summarized at a Conference at SIN[13]. Limits for $\frac{\mu^+ \rightarrow e^+ + \gamma}{\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu}$ have been reported from TRIUMF[14] and SIN as $< 3.6 \times 10^{-9}$ and 1.6×10^{-9}, respectively. A LASL-Chicago-Stanford experiment now in progress expects to reach a limit of $\sim 10^{-10}$.

TABLE VI

SUMMARY OF EXPERIMENTAL LIMITS FOR ELECTRON HALF-LIVES

EXPERIMENTERS	ELECTRON LIFETIME (YR)	DETECTION METHOD	ELECTRON SOURCE
E. DER MATEOSIAN AND M. GOLDHABER, UNPUBLISHED (1958-1959)	$>10^{19}$	K X-RAYS OF IODINE	NaI CRYSTAL
	$>10^{20}$	γ RAYS FROM PROCESS $e^- \rightarrow \nu + \gamma$.	"
M. K. MOE AND F. REINES PHYS. REV. 140B, 992 (1965)	$>2 \times 10^{21}$	K X-RAYS OF IODINE	"
	$>4 \times 10^{22}$	γ RAYS FROM PROCESS $e^- \rightarrow \nu + \gamma$.	"
R. I. STEINBERG, K. KWIATKOWSKI, W. MAENHAUT, AND N.S. WALL PHYS. REV. D12, 2582 (1975)	$>5.3 \times 10^{21}$	K X-RAYS OF Ge	Ge(Li) DETECTOR

It is worth recognizing that the limit already found for the partial lifetime for $\mu \to e + \gamma$ exceeds the β-decay time of a neutron — a remarkable measurement!

At the SIN Conference[15] a limit was also reported for

$$\frac{\mu^- + S \to e^- + X}{\mu^- + S \to \nu + Y} < 4 \times 10^{-10}.$$

Some theories predict only slightly lower values. The theoretical situation was reviewed by S. Weinberg at the SIN Conference.

The recent experiments and theories connected with the possibility of nonconservation of muon number have revived interest in neutrino oscillations — another process which would not conserve L_x. This subject has just been reviewed by Bilensky and Pontecorvo[16].

REFERENCES

1) A. Pais, The Early History of the Theory of the Electron, 1897-1947, Chapter 5, in Aspects of Quantum Theory, ed. by A. Salam and E. P. Wigner, p. 79 (Cambridge University Press, 1972).

2) E. C. G. Stueckelberg, Helv. Phys. Acta 11, 299 (1939).

3) E. P. Wigner, Proc. Am. Philos. Soc. 93, 521 (1949) [see also Proc. Nat. Acad. Sci. 38, 449 (1952)].

4) F. Reines, C. L. Cowan, Jr., and M. Goldhaber, Phys. Rev. 96, 1157 (1954).

5) A. Pais, Proc. of Int. Conf. of Theor. Phys. (Kyoto), Published by Science Council of Japan, Tokyo, p. 157 (1954).

6) G. Feinberg and M. Goldhaber, Proc. Nat. Acad. Sci. 45, 1301 (1958).

7) M. Goldhaber, Proc. Am. Philos. Soc. 119, 24 (1975).

8) J. G. King, Phys. Rev. Lett. 5, 562 (1960); G. Gallinaro, M. Marinelli and G. Morpurgo, Phys. Rev. Lett. 38, 1255 (1977).

9) J. C. Pati and A. Salam, Phys. Rev. Lett. 31, 661 (1973).

10) See, e.g., H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438 (1974); H. Georgi, H. R. Quinn and S. Weinberg, ibid 33, 451 (1974).

11) M. Abud, F. Buccella, H. Ruegg and C. A. Savoy, Phys. Lett. 67B, 313 (1977); P. Langacker, G. Segrè and A. Weldon, U. of Penn. preprint.

12) M. Gell-Mann, P. Ramond and R. Slansky (to be published).

13) See Nature 269, 375 (1977).

14) See Depommier et al, Phys. Rev. Lett. 39, 1113 (1977).

15) See A. Badertscher et al., Phys. Rev. Lett. 39, 1385 (1977).

16) S. M. Bilensky and B. Pontecorvo, Comments on Nuclear and Particle Physics, 7, 149 (1977).