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ADDITIVE VERSUS MULTIPLICATIVE MUON CONSERVATION

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Additive versus Multiplicative Muon Conservation

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A. Introduction

The question of the nature of muon conservation had been regarded as an unsolved curiosity for well over a decade, because it was not experimentally accessible. Recent progress in experimentation has finally made it possible to elucidate the answer.

The law of conservation of leptons accounts for the absence of neutrinoless double beta decay[1] but would allow muon to electron transitions such as

$$\begin{aligned} \mu^+ &\rightarrow e^+ \gamma \\ \mu^+ &\rightarrow e^+ e^- e^+ \\ \mu^- Z &\rightarrow e^- Z . \end{aligned} \tag{1}$$

The apparent absence[2] of these transitions led to the postulation of a new conserved quantum number, "muonness"[3]. The existence of a muon number was confirmed by the neutrino experiment of Danby et al.[4] which demonstrated the distinct identity of neutrinos from pion decay (ν_μ) and neutrinos from nuclear beta decay (ν_e), by observing that

$$\nu_\mu \; Z \rightarrow Z \; \mu^- , \tag{2}$$

but

$$\nu_\mu \; Z \not\rightarrow Z \, e^- . \tag{3}$$

The possibility that muon conservation is a multiplicative law rather than an additive one, was proposed by G. Feinberg and S. Weinberg[5] and by

N. Cabbibo and R. Gatto.[6] Using the lepton numbers defined in Table I., one can require, in addition to the conservation of total lepton number,

$$\Sigma \; L = \text{constant} , \qquad (4)$$

either a new (charge-like) additive muon conservation law,

$$\Sigma \; L_\mu = \text{constant} , \qquad (5)$$

or a new (parity-like) multiplicative muon conservation law,

$$\pi \; P_\mu = \text{constant} . \qquad (6)$$

Table I. Lepton Number Assignments.

Particle	L	L_e	L_μ	P_μ
e^-, ν_e	1	1	0	1
μ^-, ν_μ	1	0	1	-1
e^+, $\bar{\nu}_e$	-1	-1	0	1
μ^+, $\bar{\nu}_\mu$	-1	0	-1	-1

There exist several formally equivalent ways of writing down either the additive or multiplicative law. A symmetric phrasing of the additive law is the separate conservation of electron and muon numbers ($\Sigma \, L_e$ = constant and $\Sigma \; L_\mu$ = constant), which contains Eq. 5 and yields Eq. 4 since $L = L_e + L_\mu$. This version leads to a natural generalization for further lepton flavors, $\Sigma \; L_i$ = constant, i = e, μ, τ ..... The multiplicative law can be rewritten economically in terms of L_e and L_μ as $\pi(-1)^{L_\mu}$ = constant with $\Sigma(L_e + L_\mu)$ = constant. The symmetric formula $\pi(-1)^{L_e}$ = constant then follows as a result.[7]

The multiplicative and additive formulations are equally good a priori, since they both identically fulfill the requirement of prohibiting reactions (1) and reaction (3), but they do have different consequences. Of the two laws (5) and (6), the additive one is the more restrictive. The multiplicative law allows, but the additive law prohibits muonium-antimuonium conversion[8],

$$\mu^+ e^- \leftrightarrow \mu^- e^+ , \tag{7}$$

and muon decay with inverted subscripts on the neutrinos,

$$\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_e , \tag{8}$$

while both laws allow muon decay with the conventional subscript assignment,

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu . \tag{9}$$

The observation of reactions (7) and (8), or their transposed equivalents (such as $e^- e^- \rightarrow \mu^- \mu^-$ or $\bar{\nu}_\mu e^- \rightarrow \mu^- \bar{\nu}_e$) would signal a multiplicative law. We would then expect these two reactions to be weak interactions with a strength comparable to G_V^2. For the charged current reaction (8) the lifetime of the muon in fact puts a rigorous upper bound on the coupling. Since (8) is a partial decay mode of the muon, its branching ratio

$$R = \frac{\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_e}{\mu^+ \rightarrow \text{all}} , \tag{10}$$

is bounded by $0 \leq R \leq 1$. For the neutral current reaction (7) there is no corresponding rigorous bound. The new coupling could have a coupling strength greater than G_V^2, although this would be unexpected.

Because of the symmetric appearance of decays (8) and (9), we might expect $R \sim 0.5$ in a multiplicative scheme. However, the selection rule cannot determine the dynamics; thus a much smaller value of R has been predicted in a model theory by E. Derman.[9]

B. Neutral Currents: Muonium-Antimuonium Experiments

For a standard V-A form of the interaction the probability of $M = \mu^+ e^-$ converting to $\bar{M} = \mu^- e^+$ (Eq. 7) before decaying, in vacuo, is[10]

$$P(M \rightarrow \bar{M}) = 2.5 \times 10^{-5} (G_M/G_V)^2 , \qquad (11)$$

a respectable fraction for $G_M \sim G_V$. However, the conversion is strongly quenched in any finite density target used to form the muonium, because the degeneracy between M and $\bar{M}$ is broken by the external fields of collisions in a gas or the lattice in a crystal. The suppression factor is about $\sim 10^{-14}$ in a crystal and around 10^{-5} in a gas at 1 atmosphere[10, 11].

It would certainly be desirable to look for $M \rightarrow \bar{M}$ conversion in a vacuum. Evidence for the observation of thermal muonium using thin gold foils in a vacuum has been reported by B.A. Barnett et al.[12] No formation of thermal muonium in a vacuum from thin foils was seen, however, in a similar experiment by W. Beer et al.[13] P. Bolton et al.[14] have presented evidence for production of fast muonium emerging into vacuum from a single foil.

J.J. Amato et al.[15] have carried out a search for $M \rightarrow \bar{M}$ conversion in argon gas at the Nevis cyclotron. A μ^+ beam was stopped in a 1 atm. Ar target, to form

$\mu^+ e^-$. Upon conversion to $\mu^- e^+$ the μ^- would be captured to form a muonic argon atom. The experiment therefore used the 2P → 1S mu-mesic argon x-ray to signal the conversion process. In this gas target the probability of conversion was

$$P(M \rightarrow \bar{M}) = 1.0 \times 10^{-10} \, (G_M/G_V)^2 \, .$$

No antimuonium signal was seen in $5 \times 10^{+7}$ μ^+ stops on the target, corresponding to 4.2×10^6 muonium formations. The resulting lower limit on the coupling constant for $M \rightarrow \bar{M}$ (Eq. 7) is

$$G_M/G_V < 6800 \quad (90\% \text{ c.}\ell.) \, .$$

A search for the inverse process, $e^- e^- \rightarrow \mu^- \mu^-$, was carried out in colliding electron beams of 525 MeV/beam at the Princeton-Stanford electron storage rings by W.C. Barber et al.[16] Time-of-flight techniques were used to select beam-associated events while lead absorbers and shower chambers distinguisned muon and electron events. One $\mu^- \mu^-$ candidate passed the final selection criteria with an expected background of 3.7 ± 1.1 events. This result is consistent with no $M \rightarrow \bar{M}$ conversion and sets an upper limit

$$G_M/G_V < 610 \quad (95\% \text{ c.}\ell.) \, .$$

C. Charged Currents: Muon Decay Experiments

In order to differentiate muon decay modes (8) and (9), it is necessary to observe the neutrinos from muon decay. This became possible with the high muon fluxes at the C.P. Anderson Meson Physics Facility (LAMPF). The charged current reactions

$$\nu_e Z \rightarrow e^- X , \qquad (12)$$

and

$$\bar{\nu}_e Z \rightarrow e^+ X \qquad (13)$$

distinguish ν_e from $\bar{\nu}_e$ because of the conservation of total lepton number, (Eq. 4).

The first results on the multiplicative law branching ratio R (Eq. 10) were obtained with the Gargamelle heavy liquid bubble chamber in the CERN neutrino (antineutrino) beam, which is predominately ν_μ ($\bar{\nu}_\mu$) but has a small contamination of ν_e ($\bar{\nu}_e$) from muon and kaon decays. Using calculated ν_e and $\bar{\nu}_e$ fluxes from both sources, the observed events of reactions (12) and (13) were analyzed for the contribution of muon decay (8) and (9). Based on the analysis of 38 events T. Eichten <u>et al</u>,[17] reported $R < 0.25$ (95% confidence level). A larger sample of 200 e^- and 60 e^+ events was examined by J. Blietschau <u>et al</u>,[18] who obtained the values of R shown in Table II. If we do a weighted average of those four values, we obtain $R = 0.13 \pm 0.15$.

<u>Table II.</u> <u>Results for R from the Gargamelle Experiment</u>

ν Exposure	$\bar{\nu}$ Exposure
Excess e^+ : $R = 0.1 \pm 0.3$	Excess e^- : $R = 0.2 \pm 0.2$
Lack of e^- : $R = 0.00 \pm 0.6$	Lack of e^+ : $R = 0.3 \pm 0.6$

The neutrinos from a pure source of μ^+ decays at rest were observed in a neutrino experiment at LAMPF by a Yale/LASL/Saclay/SIN/Bern/NRC collaboration.[19] The μ^+ originated from π^+ decay in the primary proton beam stop where the π^- were captured before decaying into μ^-. A six-ton water Cerenkov counter[20] filled alternately with water and heavy water, was used to observe $\bar{\nu}_e$ and ν_e by the elastic inverse beta decay reactions

$$\bar{\nu}_e \; p \; \rightarrow \; n \; e^+ \tag{14}$$

on the free protons in H_2O, and

$$\nu_e \; d \; \rightarrow \; pp \; e^- \tag{15}$$

on the deuterons in D_2O. The free proton in reaction (14) identified $\bar{\nu}_e$, since charge conservation prevents ν_e p inverse beta decays. Neutrino events on oxygen were a negligible background because of Pauli exclusion principle effects; muon neutrinos were below the charged current energy threshold.

Figures 1. and 2. show the beam-associated signal for D_2O and H_2O runs with 400 and 1000 coulombs of protons, respectively. Low energy neutron backgrounds are rejected by a 25 MeV energy cut. Fig. 1. shows a 250 event neutrino signal in the D_2O; no corresponding signal is seen in the H_2O run, (Fig. 2.). Comparison of the two spectra yields the value of

$$R = 0.00 \pm 0.06$$

and clearly points to an additive law.

Neutrino induced inverse muon decay is an alternate way to search for nonzero R. C.Y. Chang[21] obtained an upper limit of $G_M < 5\, G_V$ (corresponding to a non-physical limit of $R < 25$) for the reaction $\nu_\mu \, Z \rightarrow \mu^+ \, e^- \, \nu_e \, Z$ in a CERN neutrino beam. M. Jonker et al.[22] have used the CHARM neutrino detector in the CERN wide band neutrino beam to compare the rate of $\bar{\nu}_\mu e^- \rightarrow \mu^- \bar{\nu}_e$ (corresponding to Eq. 8) with that of $\nu_\mu e^- \rightarrow \mu^- \nu_e$ (corresponding to Eq. 9) and reported $R < 0.09$ (90% confidence level). Table III. summarizes the experimental limits on R in chronological order.

Table III. Limits on Multiplicative Law Parameter R

Chang	1970	$R < 25$
Gargamelle	1973	$R < 0.25$, 95% c.ℓ.
Gargamelle	1978	$R = 0.13 \pm 0.15$ ($R < 0.34$, 90% c.ℓ.)
Yale/LASL	1980	$R = 0.00 \pm 0.06$ ($R < 0.10$, 90% c.ℓ.)
CHARM	1980	$R < 0.09$, 90% c.ℓ.

D. Conclusions

The neutral current experiments have not yet yielded information about mounium-antimuonium conversion at the weak interaction level.

In the charged current experiments we now have a clear picture. All the experiments agree that there is no evidence for a multiplicative law. The best limits, from the muon decay neutrino experiment at LAMPF and from the inverse muon decay experiment in the CERN neutrino beam, definitely exclude multiplicative law schemes with $R \sim \frac{1}{2}$.

Unless the dynamics conspire to make a multiplicative law with very small R we appear to live in a world with separately conserved additive lepton flavors.

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Figure Captions

1. Yale/LASL experiment neutrino spectrum: D_2O.
2. Yale/LASL experiment neutrino spectrum: H_2O.

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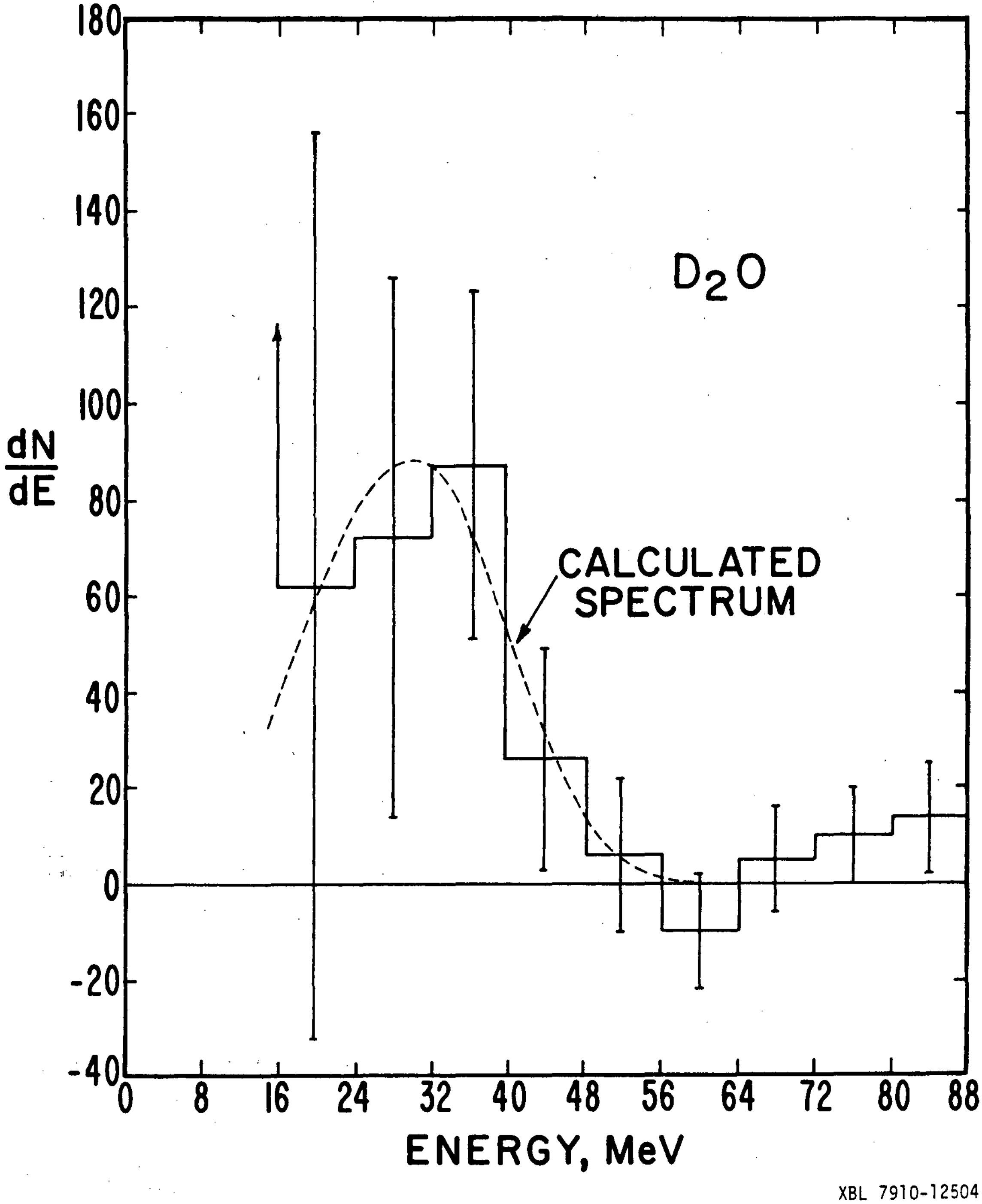

180
160
140
120
100
80
60
40
20
0
-20
-40
dN/dE
D2O
CALCULATED SPECTRUM
0 8 16 24 32 40 48 56 64 72 80 88
ENERGY, MeV
XBL 7910-12504

Fig. 1

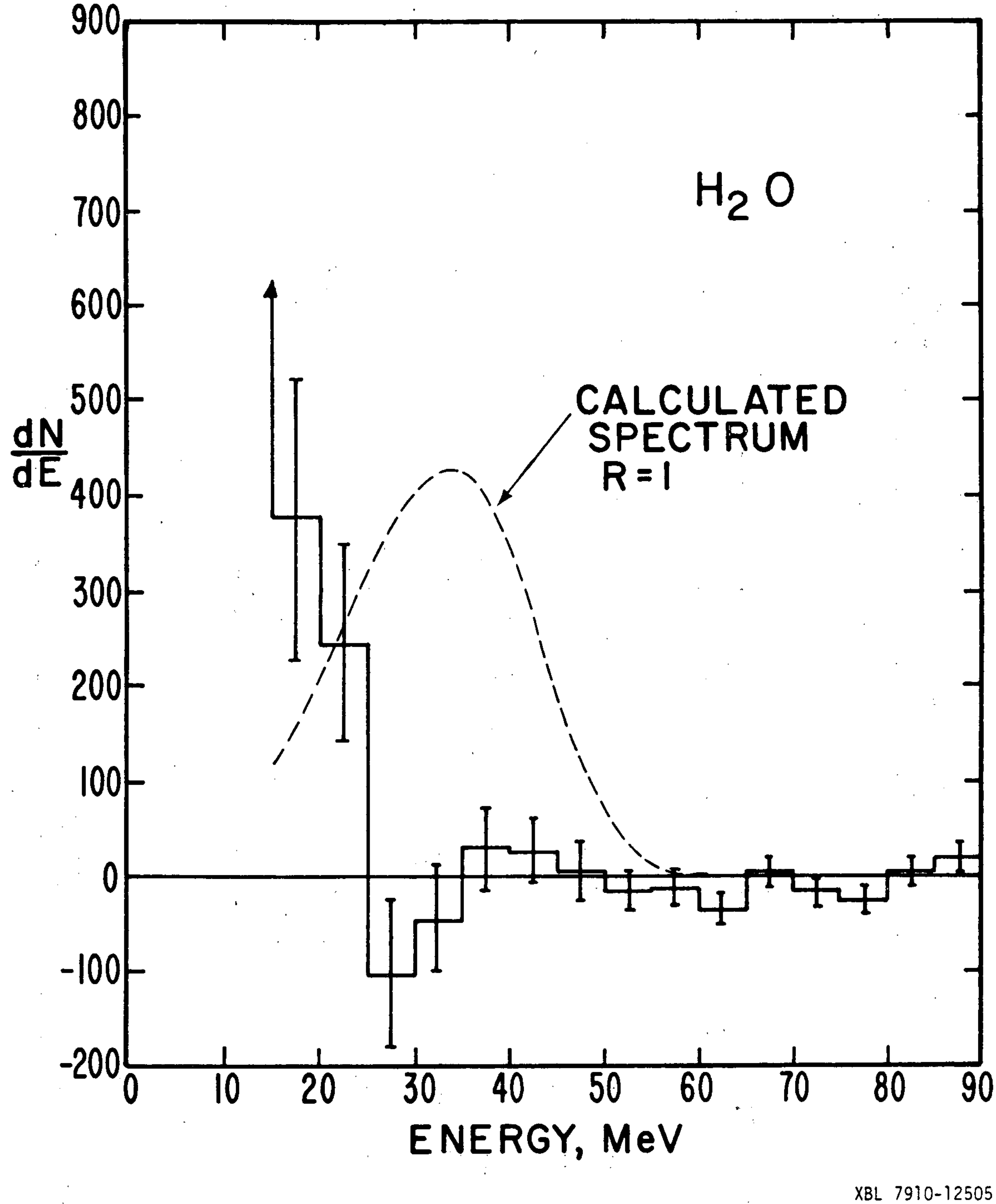
H2 O
CALCULATED
SPECTRUM
R = 1
dN/dE
900
800
700
600
500
400
300
200
100
0
-100
-200
0
10
20
30
40
50
60
70
80
90
ENERGY, MeV
XBL 7910-12505

Fig. 2

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