Laurie Littenberg: a Remarkable Physicist

Robert Shrock

C. N. Yang Institute for Theoretical Physics, Stony Brook University

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Outline

- Measurement of $K^+ \to \pi^+\nu\bar{\nu}$ decay
- Upper bounds on $|\Delta L| = 2$ meson and baryon decays
- Searches for heavy neutrino emission via mixing in $\pi^+_{\ell 2}$ and $K^+_{\ell 2}$ decays
- Ending remarks

Measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ Decay

It is a great privilege and pleasure to contribute to this celebration of Laurence Littenberg's career and accomplishments.

I have known Laurie since the 1970s and have had many very valuable and fruitful interactions with him. I regard him as a remarkable physicist for many reasons.

As discussed by Doug Bryman and Stew Smith, Laurie played a leading role in obtaining the first measurement of the rare K decay $K^+ \to \pi^+ \nu\bar{\nu}$, as cospokesman of BNL E787 (S. Adler et al. (E787 Collab.), PRL 79, 2204 (1997); PRL 84, 3768 (2000); PRL 88, 041803 (2002)). This was recognized by the award of the 2011 Panofsky Prize to Laurie, Doug, and Stew for this tremendously impressive achievement.

Doug, Steve Kettell, Laurie, and their collaborators carried on this work in the successor experiment BNL E949. The current measured value based on data from both experiments is

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \ (90\% \ CL)$$

(V. Anisimovsky et al. (E949 Collab.) PRL 93, 031801 (2004); Artamonov et al. (E949) PRL 101, 191802 (2008)), in agreement with the Standard-Model (SM), $(0.8 \pm 0.1) \times 10^{-10}$. This is a stringent test of the SM and the unitarity of the CKM quark mixing matrix, and a valuable constraint on possible beyond-SM (BSM) physics.

Appeal of $K^+ \to \pi^+ \nu\bar{\nu}$ (i.e., $\sum_{\nu_e,\nu_\mu,\nu_\tau} K^+ \to \pi^+ + \nu_\ell \bar{\nu}_\ell$) decay: hadronic part of the matrix element is related to the known matrix element for $K_{\ell 3}$ decay, and process is short-distance dominated, so BR can be rather accurately calculated.

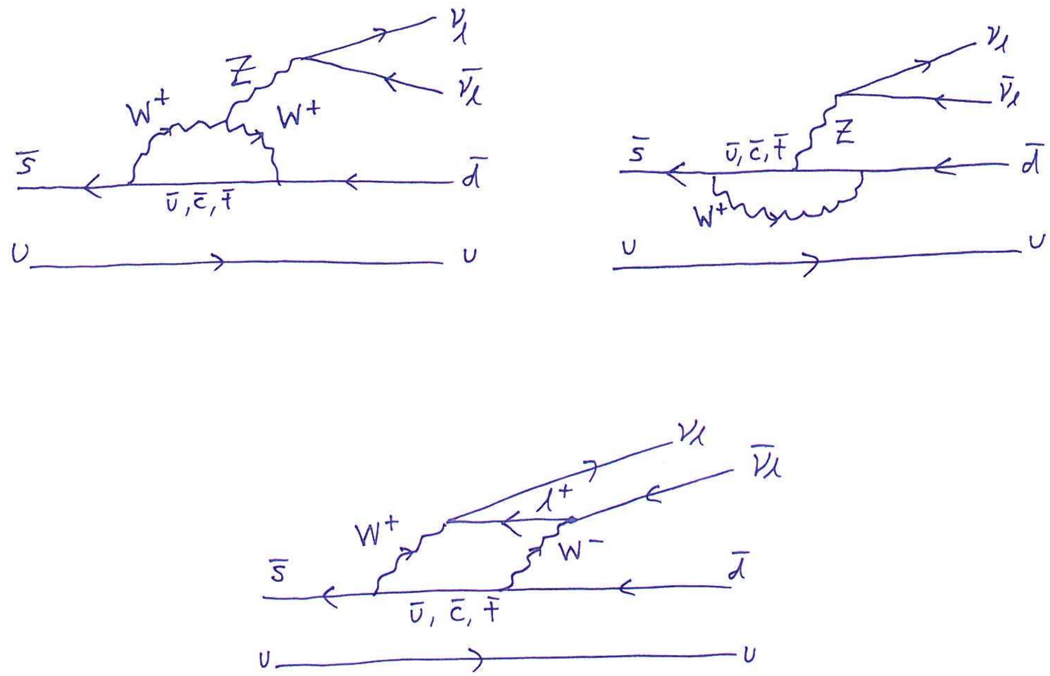
Early study of one-loop induced K decays and $K - \bar{K}$ mixing by M. K. Gaillard and B. W. Lee (Phys. Rev. D10, 897 (1974)) showed GIM mechanism operates at the one-loop level to strongly suppress these flavor-changing neutral current (FCNC) processes.

Gaillard and Lee estimated $BR(K^+ \to \pi^+ \nu\bar{\nu}) \simeq 10^{-10}$, showed how challenging a measurement of this decay would be because of the extremely small BR.

Additional challenge: two of the final-state particles are not observed, so must have an extremely good detector that can suppress/veto possible backgrounds.

Laurie was courageous enough to take up this challenge and was so skilled, dedicated, and perseverent, that, with his collaborators, he met the challenge, designed, built, and ran the experiment, and successfully measured this decay with its tiny branching ratio. This was truly a great achievement.

Further appeal of an experiment on $K^+ \to \pi^+ +$ missing (weakly interacting) neutrals: since the BR for the SM decay $K^+ \to \pi^+ \nu\bar{\nu}$ is so small, this provides excellent opportunity to search for BSM physics.



GRAPHS FOR $K^+ \to \pi^+ \nu\bar{\nu}$ IN SM

Upper limit as of 1981: $BR(K^+ \to \pi^+\nu\bar{\nu}) < 1.4 \times 10^{-7}$ at 90 % CL (Asano et al. (KEK), Phys. Lett. 107B, 159 (1981)). So large window for the discovery of possible BSM physics that might contribute above the SM level $BR \simeq 10^{-10}$.

Several possible BSM contributions; e.g., in SUSY (i) new contributions to internal lines in the one-loop diagrams contributing to $K^+ \to \pi^+\nu\bar{\nu}$ and (ii) new decay modes with the same experimental signature.

Early SUSY studies considered the possibility that photinos $\tilde{\gamma}$ (neutralinos $\tilde{\chi}$) could be light, so that the decay $K^+ \to \pi^+\tilde{\gamma}\tilde{\gamma}$ $(K^+ \to \pi^+\tilde{\chi}_1^0\tilde{\chi}_1^0)$ could occur, e.g.

M. K. Gaillard, Y.-C. Kao, I-H. Lee, and M. Suzuki, "$K^+ \to \pi^+\tilde{\gamma}\tilde{\gamma}$ in Spontaneously Broken Supersymmetric Models", Phys. Lett. 123B, 241 (1983).

The measurement of $BR(K^+ \to \pi^+\nu\bar{\nu})$ by Laurie and collaborators in E787 and E949, in conjunction with other information on CKM mixing matrix parameters from other experiments including CLEO, BABAR, and Belle , have demonstrated excellent agreement with the SM CKM picture and a consistent unitarity triangle. This is a very important constraint on any BSM physics.

Currently, CERN NA62 exp. is taking data on $K^+ \to \pi^+\nu\bar{\nu}$ (using decay-in-flight rather than decay-at-rest).

Laurie's deep knowledge of both experimental and theoretical physics evident in many ways, e.g., his pioneering analysis of $K_L \to \pi^0 \nu \bar{\nu}$, pointing out its potential to elucidate CP violation: L. Littenberg, Phys. Rev. D39, 3322 (1989) and later work with Doug Bryman, Mike Zeller, et al. toward KOPIO exp.

Also Laurie's lucid, authoritative talks and reviews, e.g., L. Littenberg. and G. Valencia, Ann. Rev. Nucl. Part. Sci. 43, 729 (1993) and periodically updated minireviews in the PDG Review of Particle Properties, http://pdg.lbl.gov.

With Frank Paige and others, Laurie studied searches for SUSY, contributed to planning for GEM detector for SSC.

Laurie has also given generously of his time, serving on many HEP advsory and program committees, and has continued with neutrino physics on Daya Bay, DUNE.

Another of the ways in which Laurie is a remarkable physicist is his very friendly personality, supportive and open to ideas and discussions, enthusiastic to pursue these to get new information in particle physics, always with great modesty and a wonderful sense of humor.

Upper Limits on $|\Delta L| = 2$ Meson and Baryon Decays

I have enjoyed many discussions with Laurie. We shared some common interests in K decays. After my Ph.D. (Princeton, 1975), my first paper as postdoc at Fermilab, in summer, 1975, was on $K_L \to \mu^+\mu^-$, M. Gaillard, B. W. Lee, RS, Phys. Rev. D13, 2674 (1976); others included B. W. Lee, RS, Phys. Rev. D16, 1444 (1977) with results on charged-lepton flavor violating decays $K_L \to \mu^\pm e^\mp$ and $K^+ \to \pi^+\mu^\pm e^\mp$ in theories with massive neutrinos, and bounds on CKM angles from $K_L \to \mu^+\mu$ in RS and M. Voloshin, Phys. Lett. 87B, 375 (1980).

Laurie and I collaborated on papers giving new limits on $|\Delta L| = 2$ meson and baryon decays:

1. L. S. Littenberg and RS, "Upper Bounds on Lepton-Number Meson Decays", Phys. Rev. Lett. 68, 443 (1992).
2. L. S. Littenberg and RS, "Upper Bounds on $|\Delta L| = 2$ Decays of Baryons", Phys. Rev. D46 (Rapid Commun.) R892 (1992).
3. L. S. Littenberg and RS, "Implication of Improved Bounds on $|\Delta L| = 2$ Processes", Phys. Lett. B491, 285 (2000).

Upper Bounds on Lepton-Number Violating Meson Decays

Laurence S. Littenberg[(1),(a)] and Robert E. Shrock[(2),(b)]
[(1)]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973*
[(2)]*Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794-3840*
(Received 18 September 1991)

From a retroactive data analysis, we obtain the first upper bound on the $|\Delta L|=2$ kaon decay $K^+\to\pi^-\mu^+\mu^+$: $B(K^+\to\pi^-\mu^+\mu^+)<1.5\times10^{-4}$. We also discuss $K^+\to\pi^-\mu^+e^+$ and $|\Delta L|=2$ decays of D and B mesons. We suggest experiments which can improve our limit and discuss the connection with direct searches for heavy neutrinos in $K^\pm_{\mu 2}$ decay.

PACS numbers: 13.20.Eb, 11.30.Hv, 13.20.Fc, 14.60.Gh

The related issues of the conservation of total lepton number, possible neutrino masses, and possible lepton mixing remain of fundamental importance. The decays

$$K^+\to\pi^-l^+l'^+\,, \tag{1}$$

where l and l' denote e or μ, are of interest in this regard because they violate total lepton number and lepton family number. The $\mu\mu$ mode in (1) is the most interesting here, since it is a probe of lepton-number violation which is not constrained by the stringent limits which have been set on neutrinoless double beta ($0\nu2\beta$) decay of nuclei or the conversion process $\mu^-+(Z,A)\to e^++(Z-2,A)$ [1]. To our knowledge, there has not been any report of an experimental search for, or an upper limit on, this $\mu\mu$ mode.

We have therefore carried out a retroactive analysis of data on $K^\pm$ decays for this purpose. Counter experiments which measured or searched for other decay modes had triggers which, as far as we can tell, would have excluded any events from the decay $K^+\to\pi^-\mu^+\mu^+$. As is well known, bubble-chamber experiments, as usually operated, do not have this drawback. From our examination of bubble-chamber experiments on $K^\pm$ decays, we derive the most stringent limit from the data of a Maryland-Rutgers experiment at Brookhaven National Laboratory which used the 30-in. BNL-Columbia hydrogen bubble chamber [2]. This experiment searched for $K^-\to\pi^+e^-e^-$, utilizing a sample of 65000 K^- decays. We reproduce the spectrum of $K^-\to\pi^+x^-x^-$ events from this experiment in Fig. 1 as a function of $\rho=m_x^2/m_\pi^2$ (see Ref. [2] for details of the data analysis). All (charged) three-prong events with momentum imbalance transverse to the K^- direction of <30 MeV/c were assumed to correspond to decays of the type $K^-\to\pi^+x^-x^-$. The spectrum of Fig. 1 was then calculated on this assumption. In accordance with its aim, this experiment subjected only events having $\rho\simeq m_e^2/m_\pi^2$ to a further kinematic fitting program. A Monte Carlo simulation indicates that the resolution in m_x^2 for the $\pi^+\mu^-\mu^-$ channel is about 15% worse than that for the $\pi^+\pi^-\pi^-$ channel, the resolution of which is evident from Fig. 1. The center of the distribution of possible $\pi^+\mu^-\mu^-$ events is at $\rho=0.572$; integrating the resolution function from $\rho=0.5$ to 0.65, one includes 97.7% of the entire distribution. This interval of the experimental plot includes five events. Assuming Poisson statistics, a sample of 9.27 events will fluctuate down as far as 5 events 10% of the time. Dividing the 9.27 by 0.977, we thus obtain a 90%-C.L. upper limit [3] of 9.5/65000, i.e.,

$$B(K^+\to\pi^-\mu^+\mu^+)<1.5\times10^{-4}\,. \tag{2}$$

Clearly our direct limit (2) can be greatly improved by a dedicated experiment, which we suggest. Neither of the high-sensitivity Brookhaven K^+ decay experiments E777 [4] and E787 [5] reported any limits on decays of type (1). The proposals for upgrades of these experiments, E865 and E787 (extended), do not mention any search for decays of type (1) [6]. However, with the requisite modifications, they could perform this search. Sensitivities of order 10^{-9} in branching ratio should be possible [7]. Even in advance of dedicated experiments, however, one may observe that in E787, the existing data sample can be analyzed for possible $K^+\to\pi^-\mu^+\mu^+$ events.

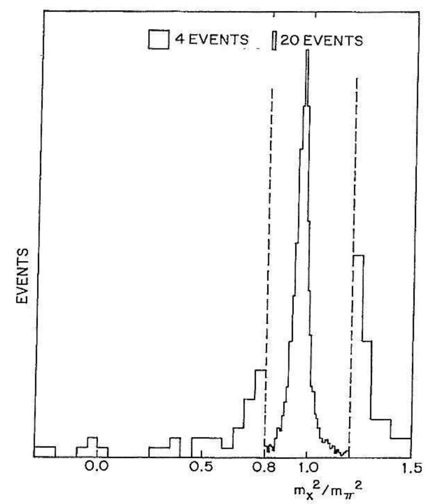


FIG. 1. The event distribution for $K^-\to\pi^+x^-x^-$, as a function of m_x^2/m_π^2 from Ref. [2].

Abstract from our 1992 PRL:

"From a retroactive data analysis, we obtain the first upper bound on the $|\Delta L| = 2$ kaon decay $K^+ \to \pi^- \mu^+ \mu^+$: $B(K^+ \to \pi^- \mu^+ \mu^+) < 1.5 \times 10^{-4}$. We also discuss $K^+ \to \pi^- \mu^+ e^+$ and $|\Delta L| = 2$ decays of D and B mesons. We suggest experiments which can improve our limit and discuss the connections with direct searches for heavy neutrinos in $K^+_{\mu 2}$ decay."

Neutrino masses and lepton mixing - first physics beyond the original Standard Model, which had zero neutrino masses and conservation of lepton family no. and total lepton no.

ν mass terms naturally include electroweak-singlet Majorana bilinear operators $\sum_{i,j} M_{R,i,j}\nu^T_{i,R}C\nu_{j,R} + h.c.$, violating total lepton no. L by $|\Delta L| = 2$.

Best current upper bounds on $|\Delta L| = 2$ decays are from searches for neutrinoless double beta ($0\nu 2\beta$) decays $(Z, A) \to (Z + 2, A) + e^- + e^-$. Amplitude $Amp \propto \sum_i U^2_{ei} f(m_{\nu_i})$. For light neutrinos, $Amp \propto \langle m_{\beta\beta}\rangle \equiv \sum_i U^2_{ei} m_{\nu_i}$.

Limits on half-lives plus approx. calc. of nuclear matrix elements (NME) yield upper limits on $\langle m_{\beta\beta}\rangle$.

2013 combined results from EXO-200 and KamLANDZen, searching for $0\nu 2\beta$ decay of ^{136}Xe yield $T_{1/2} > 3.4 \times 10^{25}$ yr. (90 % CL), $\Rightarrow$ $\langle m_{\beta\beta}\rangle < (0.12 - 0.25)$ eV, depending on NME (A. Gando et al., PRL 110, 062502 (2013)). Recently, new KamLANDZen limit: $T_{1/2} > 1.1 \times 10^{26}$ yr. $\Rightarrow$ $\langle m_{\beta\beta}\rangle < (0.06 - 0.16)$ eV (A. Gando et al., arXiv:1605.02889).

However, these limits from $0\nu 2\beta$ decays of nuclei do not constrain $|\Delta L| = 2$ decays involving muons.

More generally, independent of models, it is of interest to put limits on as many $|\Delta L| \neq 0$ process as possible, in particular, those not otherwise constrained.

Thus motivated, we investigated $|\Delta L| = 2$ pseudoscalar meson decays in our 1992 PRL, including $K^+ \to \pi^- \mu^+ \mu^+$. Previously, exps. had not searched for this decay. We examined data from previous K decay exps. to see if a retroactive analysis could yield a limit. Counter exps. had set triggers, cuts that would have excluded it in their data. We obtained our upper bound

$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 1.5 \times 10^{-4} \text{ (90\% CL)}$$

from a retroactive analysis of data from a Maryland-Rutgers BNL experiment using the 30" H bubble chamber (C. Chang, G. Yodh et al., PRL 20, 510 (1968))

We also set an indirect upper limit on the $|\Delta L| = 2$ decay $K^+ \to \pi^- \mu^+ e^+$ by using property that leptonic part of matrix elt. is related by crossing to that for the $|\Delta L| = 2$ conversion process $\mu^- + (Z, A) \to e^+ + (Z-2, A)$, for which $\sigma(\mu^- \,\mathrm{Ti} \to e^+ \,\mathrm{Ca})/\sigma(\mu^- \,\mathrm{Ti} \to \mathrm{capture}) < 1.7 \times 10^{-10}$ (S. Ahmad et al., incl. Doug Bryman (TRIUMF), PRD 38, 2102 (1988)). Hadronic matrix elements are different, but with reasonable estimate, we got

$$BR(K^+ \to \pi^- \mu^+ e^+) \lesssim \text{few} \times 10^{-9}$$

Our suggestion in the 1992 PRL to perform a dedicated search for these $|\Delta L| = 2$ K^+ decays was taken up by the BNL E865 exp. (M. Zeller, spokesman).

BNL E865 limits (R. Appel et al. (incl. H. Ma, M. Zeller..) PRL 85, 2450 (2000)) at 90 % CL:

$$BR(K^+ \to \pi^-\mu^+\mu^+) < 3.0 \times 10^{-9}$$

$$BR(K^+ \to \pi^-\mu^+e^+) < 0.50 \times 10^{-9}$$

$$BR(K^+ \to \pi^-e^+e^+) < 0.64 \times 10^{-9}$$

Improved limits from CERN NA48/2: (J. Batley et al., PLB 697, 107 (2011)):

$$BR(K^+ \to \pi^-\mu^+\mu^+) < 1.1 \times 10^{-9} \quad (90\% \text{ CL})$$

and recently from further NA48/2 data analysis (e.g., C. Lazzeroni, talk at BEACH Conf., June, 2016)

$$BR(K^+ \to \pi^-\mu^+\mu^+) < 0.86 \times 10^{-10} \quad (90\% \text{ CL})$$

In our second paper, PLB 491, 285 (2000), we studied implications of the improved limits on $|\Delta L| = 2$ decays of K^+ from BNL E865.

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Implication of improved upper bounds on $|\Delta L| = 2$ processes

Laurence S. Littenberg *, Robert Shrock [1]

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

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Abstract

We discuss implications of improved upper bounds on the $|\Delta L| = 2$ processes (i) $K^+ \to \pi^- \mu^+ \mu^+$, from an experiment at BNL, and (ii) $\mu^- \to e^+$ conversion, from an experiment at PSI. In particular, we address the issue of constraints on neutrino masses and mixing, and on supersymmetric models with R-parity violation. © 2000 Published by Elsevier Science B.V.

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At present there are increasingly strong indications for neutrino oscillations and hence neutrino masses and lepton mixing from the solar neutrino deficiency and atmospheric neutrino anomaly [1]. The existence of lepton mixing means that lepton family number is not a good symmetry. Majorana neutrino masses occur generically, and violate total lepton number L by $|\Delta L| = 2$ units. However, so far, in contrast to the data suggesting lepton mixing, experimental searches for the violation of total lepton number have only set limits. Among these are searches for the $|\Delta L| = 2$ processes (i) neutrinoless double beta $(0\nu 2\beta)$ decay of nuclei and (ii) $\mu^- \to e^+$ conversion in the field of a nucleus. A third class of $|\Delta L| = 2$ processes includes the decays $K^+ \to \pi^- \ell^+ \ell'^+$, where $\ell^+ \ell'^+ = e^+e^+$, $\mu^+ e^+$, or $\mu^+\mu^+$ [2,3]. In a previous work we considered these decays and, from a retroactive data analysis, set the first upper limit on one of them, namely [4,5],

$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 1.5 \times 10^{-4} \quad (90\%\ \mathrm{CL}). \tag{1}$$

In [4] we also noted that rare K decay experiments at BNL could greatly improve this limit and proposed a search for $K^+ \to \pi^- \mu^+ \mu^+$ [6]. Among these experiments was BNL E865, which was searching for, and has now set a stringent upper limit on, the decay $K^+ \to \pi^+ \mu^+ e^-$ [7]. This experiment has also recently obtained the 90% CL upper limit [8]

$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 3.0 \times 10^{-9}. \tag{2}$$

In the present paper we discuss the implications of this limit. In the context of current bounds on neutrinoless double beta decay and $\mu^- \to e^+$ conversion, we shall also consider the implications of two other 90% CL limits on $|\Delta L| = 2$ decays from E865 [8]:

$$BR(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10} \tag{3}$$

and

$$BR(K^+ \to \pi^- \mu^+ e^+) < 5.0 \times 10^{-10}. \tag{4}$$

* Corresponding author.
E-mail addresses: littenbe@bnl.gov (L.S. Littenberg), robert.shrock@sunysb.edu (R. Shrock).
[1] On sabbatical leave from Yang Institute for Theoretical Physics, State University of New York, Stony Brook.

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We used an improved upper bound on $\mu^- \to e^+$ conversion $\sigma(\mu^- \, \mathrm{Ti} \to e^+ \, \mathrm{Ca}_{g.s.})/\sigma(\mu^- \, \mathrm{Ti} \to \mathrm{capture}) < 1.7 \times 10^{-12}$, from J. Kaulard et al. (SINDRUM II exp. at PSI), PLB 422, 334 (1998), to infer

$$BR(K^+ \to \pi^- \mu^+ e^+) \lesssim \mathrm{few} \times 10^{-11}$$

E865 limit has advantage of being direct; further improvement in search for $\mu^- \to e^\pm$ conversion expected from $\mu 2e$ exp. at Fermilab.

One contribution to $K^+ \to \pi^- \mu^+ \mu^+$ and $K^+ \to \pi^- \mu^+ e^+$ involves neutrinos, if they are Majorana. This is negligibly small for known ν masses $\lesssim 0.05$ eV.

There might also be contribs. from possible higher-mass sterile Majorana νs (constrained by other data). For $K^+ \to \pi^- \ell^+ \ell'^+$, where $\ell^+ \ell'^+ = \mu^+ \mu^+, \ \mu^+ e^+, \ e^+ e^+$,

$$Amp(K^+ \to \pi^- \ell^+ \ell'^+) \propto \sum_j (U^*_{\ell j} U^*_{\ell' j})^2 g(m_{\nu_j})$$

where $g(\mu_{\nu_j})$ is kinematic fn., so cancellations among contribs. are possible (as in $0\nu 2\beta$ decays). (Also possible contribs. in R-parity violating SUSY.) Neutrino graphs:

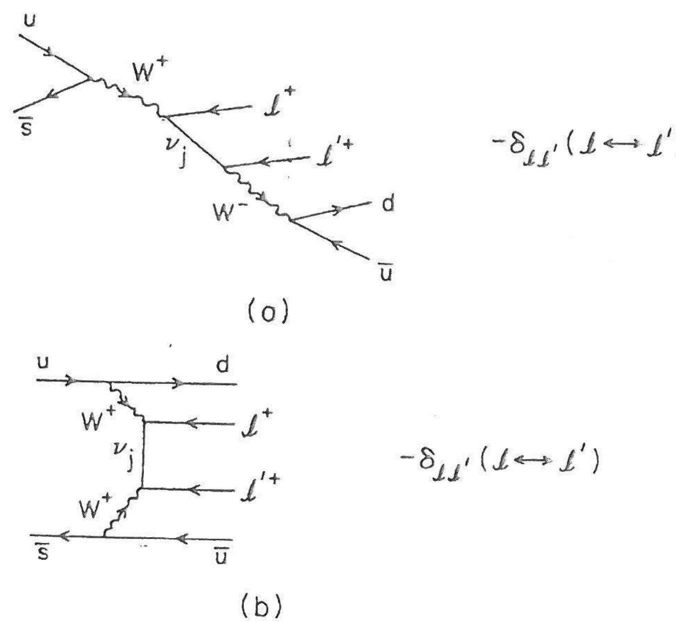

FIG. 2. Graphs contributing to $K^+ \to \pi^- l^+ l'^+$.

Some (90 % CL) upper limits on $|\Delta L| = 2$ heavy-flavor pseudoscalar meson decays:

Decay	BR Upper Lim.	Ref.
$D^+ \to \pi^-\mu^+\mu^+$	2.2×10^{-8}	R. Aaij et al. (LHCb), PLB 724, 203 (2013)
$D^+ \to \pi^-\mu^+\mu^+$	2.0×10^{-6}	J. Lees et al. (BABAR), PRD 84, 072006 (2011)
$D^+ \to \pi^-\mu^+e^+$	2.0×10^{-6}	BABAR, 2011, op. cit.
$D^+ \to K^-\mu^+\mu^+$	1.0×10^{-5}	BABAR, 2011, op. cit.
$D^+ \to K^-\mu^+e^+$	1.9×10^{-6}	BABAR, 2011, op. cit.
$D_s^+ \to \pi^-\mu^+\mu^+$	1.2×10^{-7}	LHCb, 2013, op. cit.
$D_s^+ \to \pi^-\mu^+\mu^+$	1.4×10^{-5}	BABAR, 2011, op. cit.
$D_s^+ \to \pi^-\mu^+e^+$	0.84×10^{-5}	BABAR, 2011, op. cit.
$B^+ \to \pi^-\mu^+\mu^+$	1.3×10^{-8}	R. Aaij et al. (LHCb), PRD 85, 112004 (2012)
$B^+ \to \pi^-\mu^+\mu^+$	1.07×10^{-7}	J. Lees et al. (BABAR), PRD 89, 11102 (2014)
$B^+ \to \pi^-\mu^+e^+$	1.5×10^{-7}	BABAR, 2014, op. cit.
$B^+ \to K^-\mu^+\mu^+$	4.1×10^{-8}	LHCb, 2012, op. cit.
$B^+ \to K^-\mu^+\mu^+$	6.7×10^{-8}	BABAR, 2014, op. cit.
$B^+ \to K^-\mu^+e^+$	1.5×10^{-7}	BABAR, 2014, op. cit.
$B^+ \to D^-\mu^+\mu^+$	6.9×10^{-7}	LHCb, 2012, op. cit.
$B^+ \to D^-\mu^+e^+$	1.8×10^{-6}	O. Seon et al. (Belle), PRD 84, 071106 (2011)

Laurie and I also considered $|\Delta L| = 2$ hyperon decays:

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Upper bounds on $|\Delta L|=2$ decays of baryons

Laurence S. Littenberg*
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

Robert E. Shrock†
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794-3840

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From a retroactive data analysis, we derive the first upper bound on a $|\Delta L|=2$ hyperon decay: $B(\Xi^- \to p\mu^-\mu^-) < 3.7\times 10^{-4}$ (90% C.L.). We also comment on the decay $\Sigma^- \to p\mu^-\mu^-$ and $|\Delta L|=2$ decays of charmed and b baryons, in particular, $\Xi_c^+ \to \Xi^-\mu^-\mu^-$. Finally, rough upper limits are given on $B(\Sigma^- \to p\mu^- e^-)$ and $B(\Xi^- \to p\mu^- e^-)$.

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The related issues of the conservation of total lepton number, possible neutrino masses, and possible lepton mixing continue to be of fundamental importance. An interesting class of decays which violate total lepton number L by two units is comprised of

$$B_i \to B_j l^- l'^- \tag{1a}$$

and

$$B_m \to B_n l^+ l^+ , \tag{1b}$$

where the B_i, etc., are baryons, and l and l' denote e or μ. To our knowledge, there have not been any experimental searches for, or bounds on, these decays. In the case $ll'=ee$, this is understandable, since these decay modes are not as sensitive a probe as searches for neutrinoless double β decay, which have yielded very stringent upper limits [1,2]. In the case $ll'=\mu e$, one can set an upper limit on the decay by observing that the leptonic part of the amplitude is related by crossing to the leptonic part of the amplitude for the conversion process $\mu^- + (Z,A) \to e^+ + (Z-2,A)$ (see below). Thus at present the most interesting decays of type (1) are those with $ll'=\mu\mu$, since they are not constrained by either the limits on neutrinoless nuclear double β decay or $\mu^- \to e^+$ conversion [3].

Accordingly, we have carried out a retroactive analysis of data to put an upper limit on this type of decay. In a companion paper [4] we have analyzed $|\Delta L|=2$ meson decays and have put the first upper limit on $K^+ \to \pi^-\mu^+\mu^+$. Figure 1 shows a diagram that contributes to (1a) for B_i a hyperon, together with its crossed graph for the interesting case where $l=l'$ ($=\mu$). The decays of this type are $\Sigma^- \to p\mu^-\mu^-$, $\Xi^- \to p\mu^-\mu^-$, and $\Omega^- \to \Sigma^+\mu^-\mu^-$. The rates for these decays have the quark mixing matrix dependence $|V_{ud}V_{us}|^2$ for Σ^- and $|V_{us}|^4$ for the Ξ^- and Ω^- decays, respectively, to be compared with $|V_{ud}V_{us}|^2$ for the nonleptonic hyperon decays which dominate the total decay rates. Note that the Ξ^- decay has more than three times the phase space available to the Σ^- decay (172 MeV versus 48 MeV), although it is suppressed in the rate by the factor $|V_{us}/V_{ud}|^2$ relative to the latter decay. Although the Ω^- decay has still more phase space (272 MeV), it is also mixing-angle suppressed and does not provide as powerful a probe since there are far fewer events in the world data sample.

Bubble chamber experiments are the most amenable to a retroactive search such as ours since counter experiments which measured or searched for other decay modes had triggers and cuts which, as far as we can tell, would have excluded the events of interest here. For the Ξ^- decay mode, we have obtained the most stringent limit from a retroactive analysis of a Columbia–SUNY Binghamton experiment using the 31-in. bubble chamber at BNL filled with hydrogen [5]. This experiment searched for a number of rare Ξ^- and Ξ^0 decays (and reported the first observations of the allowed weak decays $\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$ and $\Xi^0 \to \Lambda\gamma$). Among other decays, this experiment searched for the modes $\Xi^- \to p\pi^-\pi^-$ and $\Xi^- \to p\pi^- l^-\bar{\nu}_l$ for $l=e$ and μ. Events due to these decays would appear as a negative prong (the Ξ^-) which branched into three tracks. The main backgrounds were (a) elastic scattering, $K^-p \to K^-p$ followed by the decay $K^- \to \pi^+\pi^-\pi^-$, and (b) events in which the K^-p scattering did produce a Ξ^- which decayed to $\Lambda\pi^-$ with the Λ decaying in a short distance to $p\pi^-$. In order to eliminate background (a), the experiment required that candi-

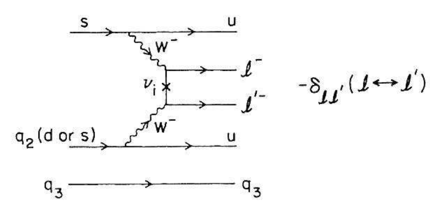

FIG. 1. Graph(s) contributing to $\Sigma^- \to pl^-l'^-$, $\Xi^- \to pl^-l'^-$, and $\Omega^- \to \Sigma^+ l^- l'^-$, for $(q_2,q_3)=(d,d)$, (s,d), (s,s), respectively.

*Electronic address: litt@bnlux1.bnl.gov.
†Electronic address: shrock@dirac.phy.sunysb.edu, shrock@sunysbnp.bitnet.

Abstract from our PLB:

"From a retroactive data analysis, we derive the first upper bound on a $|\Delta L| = 2$ hyperon decay: $BR(\Xi^- \to p\mu^-\mu^-) < 3.7 \times 10^{-4}$ (90 % CL). We also comment on the decay $\Sigma^- \to p\mu^-\mu^-$ and $|\Delta L| = 2$ decays of charmed and b baryons, in particular, $\Xi_c^+ \to \Xi^-\mu^+\mu^+$. Finally, rough upper limits are given on $BR(\Sigma^- \to p\mu^-e^-)$ and $BR(\Xi^- \to p\mu^-e^-)$."

Our limit $BR(\Xi^- \to p\mu^-\mu^-) < 3.7 \times 10^{-4}$ was obtained from a retroactive analysis of data from a Columbia-SUNY-Binghampton hydrogen bubble chamber exp. at BNL (which reported first observation of the weak decay $\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$), N. Yeh et al., PRD 10, 3545 (1974).

We suggested dedicated search for $|\Delta L| = 2$ hyperon and heavy-flavor baryon decays. This was done by the HyperCP exp. at Fermilab, which obtained the limit (D. Rajaram et al., PRL 94, 181801 (2005))

$$BR(\Xi^- \to p\mu^-\mu^-) < 4.0 \times 10^{-8} \quad (90\%\ \mathrm{CL})$$

These limits on $|\Delta L| = 2$ meson and baryon decays involving muons are useful and complement the limits from neutrinoless double beta decay.

Limits on Heavy Neutrino Emission in π^+_{e2} and $K^+_{\mu2}$ Decays

Laurie Littenberg and collaborators have recently set important new limits on heavy neutrino emission in $\pi^+ \to e^+\nu_e$ and $K^+ \to \mu^+\nu_\mu$ decays:

- TRIUMF PIENU exp.: M. Aoki et al. (incl. Laurie, Doug Bryman, Steve Kettell, Toshio Numao...), “Search for Massive Neutrinos in the Decay $\pi \to e\nu$”, PRD 84, 052002 (2011) [arXiv:1106.4055].
- TRIUMF PIENU exp.: A. Aguilar-Arevalo et al. (incl. Laurie, Doug Bryman, Steve Kettell, Toshio Numao...), “Improved Measurement of the $\pi \to e\nu$ Branching Ratio”, PRL 115, 071801 (2015) [arXiv:1506.05845].
- BNL E949 exp., A. V. Artamonov et al. (incl. Laurie, Doug Bryman Milind Diwan, Dave Jaffe, Steve Kettell, Toshio Numao, Bob Tschirhart...), “Search for heavy neutrinos in $K^+ \to \mu^+\nu_H$ decays”, Phys. Rev. D91, 052001 (2015) [arXiv:1411.3963].

Search for massive neutrinos in the decay $\pi \rightarrow e\nu$

M. Aoki,[1] M. Blecher,[2] D. A. Bryman,[3] S. Chen,[4] M. Ding,[4] L. Doria,[5] P. Gumplinger,[5] C. Hurst,[3] A. Hussein,[6] Y. Igarashi,[7] N. Ito,[1] S. H. Kettell,[8] L. Kurchaninov,[5] L. Littenberg,[8] C. Malbrunot,[3] T. Numao,[5] R. Poutissou,[5] A. Sher,[5] T. Sullivan,[3] D. Vavilov,[5] K. Yamada,[1] and M. Yoshida[1]

(PIENU Collaboration)

[1]*Physics Department, Osaka University, Toyonaka, Osaka, 560-0043, Japan*
[2]*Virginia Tech., Blacksburg, Virginia, 24061, USA*
[3]*Department of Physics and Astronomy, University of British Columbia, Vancouver, B.C., V6T 1Z1, Canada*
[4]*Department of Engineering Physics, Tsinghua University, Beijing, 100084, China*
[5]*TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., V6T 2A3, Canada*
[6]*University of Northern British Columbia, Prince George, B.C., V2N 4Z9, Canada*
[7]*KEK, 1-1 Oho, Tsukuba-shi, Ibaraki, 3050801, Japan*
[8]*Brookhaven National Laboratory, Upton, New York, 11973-5000, USA*
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Evidence of massive neutrinos in the $\pi^+ \rightarrow e^+\nu$ decay spectrum was sought with the background $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain highly suppressed. Upper limits (90% C.L.) on the neutrino mixing matrix element $|U_{ei}|^2$ in the neutrino mass region 60–129 MeV/c^2 were set at the level of 10^{-8}.

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I. INTRODUCTION

A natural extension of the standard model (SM) incorporating neutrino mass and possibly explaining the origin of dark matter involves the inclusion of sterile neutrinos mixing with the ordinary neutrinos [1]. The weak eigenstates ν_{χ_k} of such neutrinos are related to the mass eigenstates ν_i by a unitary matrix, $\nu_\ell = \Sigma_{i=1}^{3+k} U_{\ell i}\nu_i$, where $\ell = e, \mu, \tau, \chi_1, \chi_2 \ldots \chi_k$. An example of a sterile neutrino model is the neutrino minimal standard model that adds to the SM three massive gauge-singlet fermions (sterile neutrinos) [2]. In the context of this model, a search for extra peaks in the $\pi^+ \rightarrow e^+\nu$ decay spectrum is sensitive to sterile neutrinos depending on the mass hierarchy structure and choice of parameters [3]. However, the result of the search is also applicable to other types of neutrinos [4].

The decay $\pi^+ \rightarrow e^+\nu$ ($E_{e^+} = 69.8$ MeV) with a branching ratio of $R = (1.230 \pm 0.004) \times 10^{-4}$ [5–7] is helicity-suppressed by $(m_e/m_\mu)^2$ in the SM. The relaxation of this condition for massive neutrinos facilitates the search for extra peaks in the lower positron energy region. Previous results [8] at the level of $|U_{ei}|^2 < 10^{-7}$ in the neutrino mass region of 70–130 MeV/c^2 were limited by the presence of unsuppressed $\mu^+ \rightarrow e^+\nu\bar{\nu}$ decay background ($E_{e^+} = 0.5$–52.8 MeV) originating from decay-in-flight of pions [5]. The TRIUMF PIENU experiment [9] aiming at a more precise measurement of the branching ratio R was designed to further reduce this background.

In this paper, we present results of the search for low-energy peaks in the background-suppressed spectrum of $\pi^+ \rightarrow e^+\nu$ decays at rest.

II. EXPERIMENT

The extension of the TRIUMF M13 beam line [10], which suppressed positrons in the beam to <2% of pions, delivered a 75 ± 1 MeV/c pion beam to the experiment. Figure 1 shows a schematic view of the detector. The π^+ beam was degraded by two thin plastic scintillators B1 and B2 (6 mm and 3 mm thick, respectively) and stopped in an 8-mm thick active target (B3) at a rate of $5 \times 10^4 \pi^+$/s.

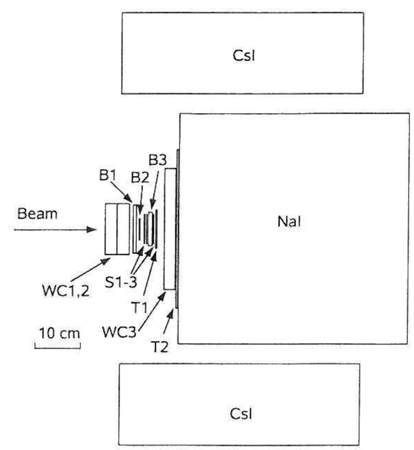

FIG. 1. PIENU Detector (see text).

Search for heavy neutrinos in $K^+ \to \mu^+ \nu_H$ decays

A. V. Artamonov,[1] B. Bassalleck,[2] B. Bhuyan,[3,†] E. W. Blackmore,[4] D. A. Bryman,[5] S. Chen,[6,4] I-H. Chiang,[3] I.-A. Christidi,[7,‡] P. S. Cooper,[8] M. V. Diwan,[3] J. S. Frank,[3,§] T. Fujiwara,[9] J. Hu,[4] J. Ives,[5] A. O. Izmaylov,[10] D. E. Jaffe,[3] S. Kabe,[11,*] S. H. Kettell,[3] M. M. Khabibullin,[10] A. N. Khotjantsev,[10] P. Kitching,[12] M. Kobayashi,[11] T. K. Komatsubara,[11] A. Konaka,[4] Yu. G. Kudenko,[10,13,14] L. G. Landsberg,[1,*] B. Lewis,[2] K. K. Li,[3] L. S. Littenberg,[3] J. A. Macdonald,[4,*] J. Mildenberger,[4] O. V. Mineev,[10] M. Miyajima,[15] K. Mizouchi,[9] N. Muramatsu,[16,∥] T. Nakano,[16] M. Nomachi,[17] T. Nomura,[9,¶] T. Numao,[4] V. F. Obraztsov,[1] K. Omata,[11] D. I. Patalakha,[1] R. Poutissou,[4] G. Redlinger,[3] T. Sato,[11] T. Sekiguchi,[11] A. T. Shaikhiev,[10] T. Shinkawa,[18] R. C. Strand,[3] S. Sugimoto,[11,*] Y. Tamagawa,[15] R. Tschirhart,[8] T. Tsunemi,[11,**] D. V. Vavilov,[1,††] B. Viren,[3] Zhe Wang,[6,3] Hanyu Wei,[6] N. V. Yershov,[10] Y. Yoshimura,[11] and T. Yoshioka[11‡‡]

(E949 Collaboration)

[1]*Institute for High Energy Physics, Protvino, Moscow Region, 142 280, Russia*
[2]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA*
[3]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[4]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[5]*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[6]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[7]*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, USA*
[8]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[9]*Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan*
[10]*Institute for Nuclear Research RAS, 60 October Revolution Prospect 7a, 117312 Moscow, Russia*
[11]*High Energy Accelerator Research Organization (KEK), Oho, Tsukuba, Ibaraki 305-0801, Japan*
[12]*Centre for Subatomic Research, University of Alberta, Edmonton T6G 2N5, Canada*
[13]*Moscow Institute of Physics and Technology, 141700 Moscow, Russia*
[14]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia*
[15]*Department of Applied Physics, Fukui University, 3-9-1 Bunkyo, Fukui, Fukui 910-8507, Japan*
[16]*Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[17]*Laboratory of Nuclear Studies, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan*
[18]*Department of Applied Physics, National Defense Academy, Yokosuka, Kanagawa 239-8686, Japan*

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Evidence of a heavy neutrino, ν_H, in the $K^+ \to \mu^+ \nu_H$ decays was sought using the E949 experimental data with an exposure of 1.70×10^{12} stopped kaons. With the major background from the radiative $K^+ \to \mu^+ \nu_\mu \gamma$ decay understood and suppressed, upper limits (90% C.L.) on the neutrino mixing matrix element between the muon and heavy neutrinos, $|U_{\mu H}|^2$, were set at the level of 10^{-7} to 10^{-9} for the heavy neutrino mass region 175 to 300 MeV/c^2.

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I. INTRODUCTION

With the neutrino masses and their mixing confirmed (see Refs. [1–16] and references therein), a natural extension of the Standard Model (SM) involves the inclusion of sterile neutrinos which mix with ordinary neutrinos to explain phenomena that may be inconsistent with the Standard Model. An example of such a theory is the neutrino minimal Standard Model (νMSM) [17,18]. In this model, three massive right-handed neutrinos are introduced to explain simultaneously neutrino oscillations, dark matter and the baryon asymmetry of the Universe.

*Deceased.
†Now at Department of Physics, Indian Institute of Technology Guwahati, Guwahati, Assam, 781 039, India.
‡Now at Physics Department, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece.
§Now at 1 Nathan Hale Drive, Setauket, New York, 11733, USA.
∥Now at Research Center for Electron Photon Science, Tohoku University, Taihaku-ku, Sendai, Miyagi 982-0826, Japan.
¶Now at High Energy Accelerator Research Organization (KEK), Oho, Tsukuba, Ibaraki 305-0801, Japan.
**Now at Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan.
††Now at TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada.
‡‡Now at Department of Physics, Kyushu University, Higashi-ku, Fukuoka 812-8581, Japan.

To set the context: we now have a wealth of data on neutrino masses and mixing from the Davis Cl exp., Kamiokande, SAGE, GALLEX, SuperK, SNO, K2K, KamLAND, Borexino, MINOS, T2K, ICARUS, NOvA, Daya Bay, RENO, Chooz, EXO-200, KamLANDZen, etc. Exps. have measured many of the relevant parameters:

$$\Delta m^2_{21} \simeq 0.75 \times 10^{-4}\ \mathrm{eV}^2$$
$$|\Delta m^2_{32}|,\ |\Delta m^2_{31}| \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$$
$$\theta_{23} \simeq 45^\circ, \quad \theta_{12} \simeq 33^\circ, \quad , \theta_{13} \simeq 9^\circ$$

More exps. planned and underway (FNAL SBL program, MINERVA, μBooNE, LBNE/DUNE, HyperK, JUNO, SHiP...); information still to be obtained includes:

- neutrino mass ordering (normal: $m_{\nu_3} > m_{\nu_2} \gtrsim m_{\nu_1}$ or inverted: $m_{\nu_2} \gtrsim m_{\nu_1} > m_{\nu_3}$)
- leptonic CP violation, δ_{CP}
- Majorana vs. Dirac nature of neutrinos

Data from most exps. fit the 3-neutrino framework.

Appealing explanation for small neutrino masses via the GUT-scale seesaw mechanism: although Dirac mass terms

$$\sum_{\ell,i} \bar{\nu}_{\ell,L} M_{D,\ell,i} \nu_{i,R} + h.c.$$

result from electroweak symmetry breaking (EWSB) and hence are naturally $<$ EWSB scale, Majorana mass terms

$$\sum_{i,j=1}^{n_s} M_{R,ij} \nu_{i,R}^T C \nu_{j,R} + h.c.$$

are SM-singlet operators. Hence, from top-down viewpoint, elts. of M_R are naturally $\gg$ EWSB scale, so (assuming $\det(M_R) \neq 0$ so M_R^{-1} exists) neutrino mass eigenvalues from diagonalization of $M_D M_R^{-1} M_D^T$ are naturally small.

Then neutrino mass eigenvalues divide into a set of small ones generically $\sim m_D^2/m_R$, and large ones $\sim m_R \sim M_{GUT}$ (or more generally, deep UV scale).

But note important scaling property: $M_D M_R^{-1} M_D^T$ is invariant under the rescaling

$$M_D \to z M_D, \quad M_R \to z^2 M_R$$

which enables a low-scale seesaw, with the mainly EW-singlet (sterile) neutrino mass eigenstates at masses $\ll M_{GUT}$.

Well-known hints of possible intermediate-mass sterile neutrinos from

- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ osc.)
- MiniBooNE ($\bar{\nu}_\mu$ data), partially consistent with LSND
- reactor $\bar{\nu}_e$ flux recalculations
- ^{51}Cr calibration anomaly in SAGE, GALLEX

These are not persuasive, but motivate further checks.

These effects hint at possible $\Delta m^2 \sim 0.1 - \mathrm{few}$ eV^2, hence new ν mass eigenstate(s), primarily EW-singlet, i.e., sterile.

Some recent global fits: Kopp, Machado, Maltoni, Schwetz, JHEP 1305, 050 (2013) [arXiv:1303.3011v3]; Giunti, Laveder, Li, PRD 88, 073008 (2013) [arXiv:1308.5288]; Gonzalez-Garcia, Maltoni, Schwetz, NPB 908, 199 (2016) [arXiv:1512.06856]; also Conrad, Shaevitz, et al., 1207.4765; some tensions with sterile νs having $\sim$ eV masses; appearance vs. disappearance results.

Neutrinos with $m_\nu \sim$ few keV can provide warm dark matter of interest to cosmology. Report of line with $E_\gamma = 3.5$ keV in X-ray data: Bulbul et al., Ap. J. 789, 13 (2014); Boyarsky et al. PRL 113, 251301 (2014), which could be due to decay $\nu_h \to \nu_i \gamma$ of a

ν_h with $m_{\nu_h} = 7$ keV (claim challenged by others, e.g., Anderson, Churazov, Bregman, MNRAS 452, 3905 (2015)).

Astrophysics/cosmological constraints on ν_h couplings, lifetime from mean mass density, BBN, CMB.

Hints of possible eV-scale and/or keV-scale ν_h also hint that possible heavier ν_hs might exist.

Low-scale seesaw models can yield intermediate mass sterile neutrinos, e.g., in $O(10^2)$ MeV to GeV region (e.g., Canetti, Drewes, Frossard, Shaposhnikov, PRD 87, 093006 (2013); Appelquist, RS PLB 548, 204 (2002); PRL 90, 201801 (2003); Appelquist, Piai, RS, PRD 69, 015002 (2004), etc.

Independent of specific models, it is of general interest to search for heavy neutrinos in as wide a mass range as possible.

Experiments are crucial to settle the question of possible intermediate-mass sterile neutrinos.

Expression of weak eigenstates $\nu_\ell = \{\nu_e, \nu_\mu, \nu_\tau\}$ in terms of mass eigenstates:

$$\nu_\ell = \sum_{i=1}^{3+n_s} U_{\ell i} \nu_i$$

where $U =$ Maki-Nakagawa-Sakata-Pontecorvo (MNSP) lepton mixing matrix.

Searches for emission of heavy neutrinos ν_h via lepton mixing in various decays proposed and applied in RS, Phys. Lett. B96, 159 (1980); RS, Phys. Rev. D 24, 1232, 1275 (1981); retroactive data analysis performed using $\pi^+_{\mu 2}$, π^+_{e2}, $K^+_{\mu 2}$, and K^+_{e2} data to set upper bounds on $|U_{\mu h}|^2$ and $|U_{eh}|^2$ down to 10^{-5} in various mass ranges including intervals in $20\ \mathrm{MeV} \lesssim m_{\nu_h} \lesssim 200$ MeV (also limits from μ decay and nuclear beta decay).

2-body leptonic decay of pseudoscalar meson $M^+ \to \ell^+ \nu_\ell$ with M^+: π^+, K^+, D^+, B^+ is very clean mode: monochromatic signature with reduced momentum p_ℓ of ℓ^+ recoiling against massive ν_h.

If see signal, use value of p_ℓ to get m_{ν_h}, independent of $|U_{\ell h}|$. From m_{ν_h} and measured $BR(M^+ \to \ell^+ \nu_h)$, extract value of $|U_{\ell h}|$. If see no signal, set upper limit on $|U_{\ell h}|$ as function of m_{ν_h}.

Simple kinematics: BR for ν_h decay wrt. decay into ν's of negligibly small masses:

$$BR(M^+ \to \ell^+ \nu_h)) = \frac{\Gamma(M^+ \to \ell^+ \nu_h)}{\Gamma(M^+ \to \ell^+ \nu_\ell)} = \frac{|U_{\ell h}|^2 \, \rho(\delta_\ell^M, \delta_h^M)}{\rho(\delta_\ell^M, 0)}$$

where

$$\rho(x, y) = f_{\mathcal{M}}(x, y) \, [\lambda(1, x, y)]^{1/2}$$

$$\delta_\ell^M = \frac{m_\ell^2}{m_M^2}, \qquad \delta_h^M = \frac{m_{\nu_h}^2}{m_M^2}$$

$f_{\mathcal{M}}(x, y) = x + y - (x - y)^2$ (from matrix element squared, $|\mathcal{M}|^2$)

and 2-body phase space factor

$$[\lambda(1, x, y)]^{1/2} = \left[1 + (x - y)^2 - 2(x + y)\right]^{1/2}$$

Define reduced functions relative to $m_{\nu_h} = 0$ case:

$$\bar{f}_{\mathcal{M}} = \frac{f_{\mathcal{M}}(\delta_\ell^M, \delta_h^M)}{f_{\mathcal{M}}(\delta_\ell^M, 0)} = \frac{f_{\mathcal{M}}(\delta_\ell^M, \delta_h^M)}{\delta_\ell^M(1 - \delta_\ell^M)}$$

$$\bar{\lambda}^{\;1/2} = \frac{\lambda^{1/2}(1, \delta_\ell^M, \delta_h^M)}{\lambda^{1/2}(1, \delta_\ell^M, 0)} = \frac{\lambda^{1/2}(1, \delta_\ell^M, \delta_h^M)}{(1 - \delta_\ell^M)}$$

$$\bar{\rho}(\delta_\ell^M, \delta_h^M) \equiv \frac{\rho(\delta_\ell^M, \delta_h^M)}{\rho(\delta_\ell^M, 0)}$$

with $\rho(x, 0) = x(1 - x)^2$ and

$$\Gamma(M^+ \to \ell^+ \nu_\ell) = \frac{|V_{qq'}|^2 \, G_F^2 \, f_M^2 m_M^3}{4\pi} \, \rho(\delta_\ell^M, 0) = \frac{|V_{qq'}|^2 \, G_F^2 \, f_M^2 m_M m_\ell^2}{4\pi} \left(1 - \frac{m_\ell^2}{m_M^2}\right)^2$$

where $V_{qq'} = V_{us}$ for K^+, etc.

Plots of reduced functions (from RS, 1981)

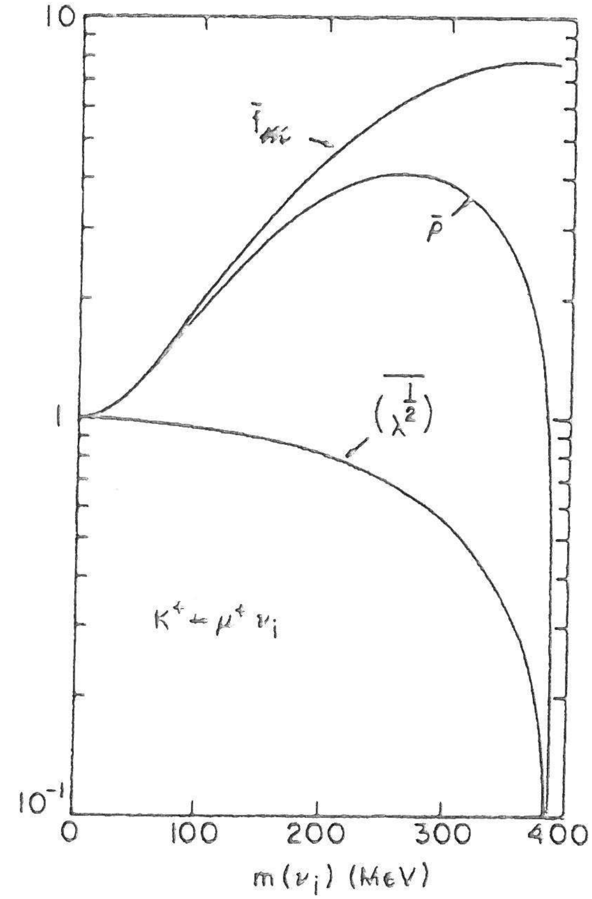

FIG. 4. Same as Fig. 2 but for the decay $K^+ \to \mu^+ \nu_i$.

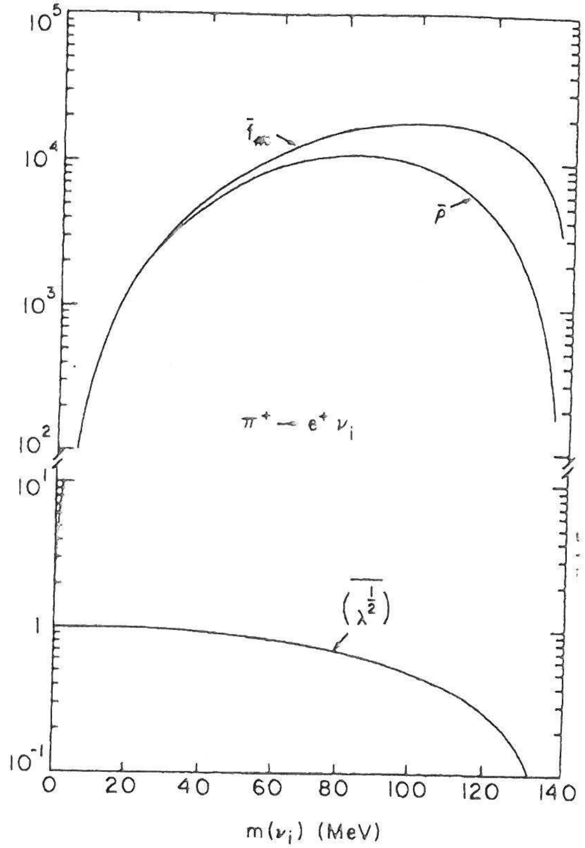

FIG. 3. Same as Fig. 2 but for the decay $\pi^+ \rightarrow e^+ \nu_i$.

Very large enhancement in the kinematic rate factor for $\pi^+ \to e^+\nu_h$ and $K^+ \to e^+\nu_h$ relative to decays to negligible-mass eigenstates in ν_e because of the removal of helicity suppression factor.

Function $f_{\mathcal{M}}$ reaches a maximum at

$$\delta_h^M = \frac{1}{2} + \delta_\ell^M$$

which is in the physical region for π^+_{e2}, K^+_{e2}, and $K^+_{\mu 2}$. Here

$$\frac{f_{\mathcal{M},max}}{f_{\mathcal{M}}(\delta_\ell, 0)} = \frac{\delta_\ell + \frac{1}{4}}{\delta_\ell(1-\delta_\ell)}$$

This ratio is $\simeq 1/(4\delta_e) \gg 1$ for $M^+ \to e^+\nu_h$ decays. Its value is 2×10^4 for $\pi^+ \to e^+\nu_h$ and 2×10^5 for $K^+ \to e^+\nu_h$.

With slow decrease of the 2-body phase space factor, relative rate factor for π^+_{e2}, $\bar{\rho}(\delta_e^\pi, \delta_h^\pi)$, reaches a max. of 1.1×10^4 at $m_{\nu_h} = 81$ MeV.

Monochromatic nature of signal and this enhancement enable one to get very stringent upper bounds on $|U_{\ell h}|^2$.

The suggested search for emission of a heavy ν_h has been carried out in a number of experiments starting in 1981 and extending to the present, including

- searches for $\pi^+ \to \mu^+ \nu_h$ in series of exps. at SIN/PSI, TRIUMF, IUCF: Abela et al., PLB 105, 263 (1981); Minehart et al., PRL 52, 804 (1984); Daum et al., PRD 36, 2624 (1987); Calaprice et al., PLB 106, 175 (1981); Bryman and Numao, PRD 53, 558 (1996); Daum et al., PRL 85, 1815 (2000).
- search for $K^+ \to \mu^+ \nu_h$ at KEK: Asano et al., PLB 104, 84 (1981); Hayano et al., PRL 49, 1305 (1982); at BNL: Artamonov et al. (E949), PRD 91, 052001 (2015); ongoing data analysis in CERN NA62.
- search for $K^+ \to e^+ \nu_h$ at KEK: Yamazaki, 1984 (ν-84 Conf.).
- searches for $\pi^+ \to e^+ \nu_h$ in a series of exps. at TRIUMF and SIN/PSI and limits from $BR(\pi^+_{e2})/BR(\pi^+_{\mu 2})$: TRIUMF exps incl. Bryman et al., PRL 50, 1546 (1983); Azuelos et al., PRL 56, 2241 (1986); Britton et al., PRD 46, R885 (1992); Aoki et al., PRD 84, 052002 (2011); Aguilar-Arevalo et al., PRL 115, 071801 (2015); SIN/PSI: DeLeener-Rosier et al. (incl. J. Deutsch, at PSI), PLB 177, 228 (1986); DeLeener-Rosier et al., PRD 43, 3611 (1991).

The TRIUMF PIENU exp. searching for $\pi^+ \to e^+ \nu_h$ obtained upper bound $|U_{eh}|^2 \lesssim \mathrm{few} \times 10^{-8}$ for $60 < m_{\nu_h} < 130$ MeV.

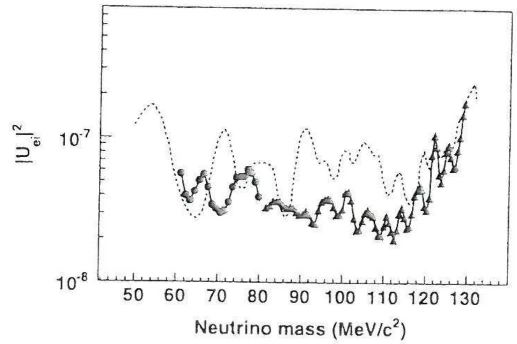

FIG. 6. Combined 90% C.L. upper limits obtained from the 35° spectrum (circles) and no-cut spectrum (triangles) together with the previous limits (dashed line) [8].

From M. Aoki et al. (PIENU Collab., TRIUMF)
PRD 84, 052002 (2011)

From A. Artamonov et al. (BNL E949 Collab) PRD 91, 052001 (2015)

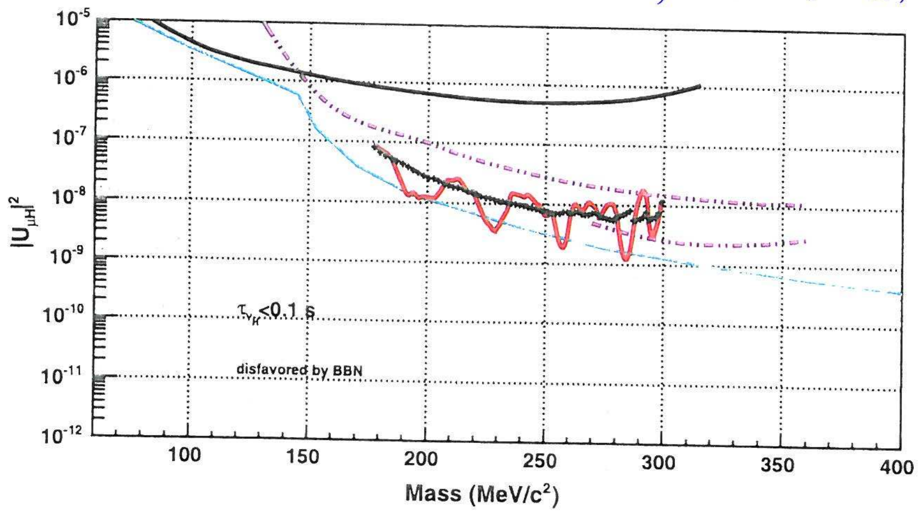

FIG. 12 (color online). 90% C.L. upper limits on the mixing matrix element $|U_{\mu H}|^2$ set by this experiment (solid red curve; black crosses show the expected upper limit) and others. The solid smooth black line shows the result of a previous peak search in kaon decays [22]. The dot-dash magenta lines show the results of the heavy neutrino decay experiment CERN PS191 [25] in two modes: the upper dot-dash line is derived from $K^+ \to \mu^+\nu_H \to \mu^+(\mu^- e^+ \nu_e) + \text{c.c.}$, and the lower dot-dash line is derived from $K^+ \to \mu^+\nu_H \to \mu^+(\mu^-\pi^+) + \text{c.c.}$ The blue shaded region shows one of the possible BBN lower bounds [34,35]. Colors are available online.

The BNL E949 exp. searching for $K^+ \to \mu^+ \nu_h$ obtained upper bound $|U_{\mu h}|^2$ from $\sim 10^{-7}$ to $\sim 10^{-9}$ for $175 < m_{\nu_h} < 300$ MeV.

Main trigger in BNL E949 exp. selected π^+ for $K^+ \to \pi^+ \nu \bar{\nu}$, but μ^+ were also present and were used for this search. The upper limits on $|U_{\mu h}|^2$ improve the old KEK limits by 10^2 factor and CERN PS191 by ~ 10, and are independent assumptions in PS191 results about ν_h couplings and lifetime.

Emission of a heavy neutrino ν_h would also shift the observed values of

$$\frac{BR(\pi^+_{e2})}{BR(\pi^+_{\mu 2})} \quad \text{and} \quad \frac{BR(K^+_{e2})}{BR(K^+_{\mu 2})}$$

from their SM values; analysis in RS (1980, 1981) and measurements of these (esp. at TRIUMF) have also yielded bounds on $|U_{eh}|^2$ of 10^{-4} to 10^{-6} for m_{ν_h} in range probed most precisely by π^+_{e2} decays. Recent TRIUMF PIENU exp. (op. cit.).

A different type of search is on the production of ν_h or $\bar{\nu}_h$ in the decay of a $\pi^{\pm}$, $K^{\pm}$, $D^{\pm}$, $D_s^{\pm}$, etc., searching for its decays $\nu_h \to \nu_i e^+ e^-$, $\nu_h \to \nu_i \mu^+ \mu^-$...

Upper bounds set on $|U_{eh}|^2$ $|U_{\mu h}|^2$, $|U_{eh} U_{\mu h}|$ via this method by the CHARM, NOMAD, BEBC, PS191, NuTeV, FMMF experiments, extending down to 10^{-6} to 10^{-8} for $100 \lesssim m_{\nu_h} \lesssim 500$ MeV, with bounds $< 10^{-7}$ for m_{ν_h} up to $\sim$ GeV from BEBC.

Further searches for heavy neutrino/neutral heavy lepton production and decay at higher masses $\sim$ GeV at LEP (Delphi, L3) and by ATLAS and up to TeV masses from LHC in ATLAS Collab., Eur. Phys.J. C72, 2056 (2012); PRL 115, 031801 (2015); CMS Collab., PRL 109, 261802 (2012); PLB 748, 144 (2015); new limits from 13 TeV LHC data...

Ending

Laurie Littenberg is truly a remarkable physicist, with outstanding experimental achievements. Let us wish him the best for his post-retirement career and hope that he continues to contribute to BNL and the HEP community his deep wisdom, excellent guidance, and pioneering research.