Neutrino history:
from the beginning of β-decay
to modern discoveries of neutrino
oscillations.

Prof. Yu. Gaponov, RRC "KI"

(Theses of the report)

(Without of references!)

Development of neutrino conception in particle physics of XX century

Yu.V.Gaponov
RRC "Kurchatov Institute", Moscow.

1. Careful study of β-spectra (1899 - 20's years)

2. Neutrino conception occures (1929 - 37)

3. Experimental observations of nuclei and particles β-decays (30's - 50's years)

4. Theoretical discoveries of 50's, Standard model (SM) delivery (1955 - 67)

5. Experimental statement of the SM (50's - 70's y.)

6. Theoretical generalization of the SM - Grand Unification Theory and return to Majorana neutrino idea (80's years)

7. In search for an exit beyond SM - experiments (80's - 90's years)

8. Conclusion: Neutrino physics on the threshold of the new century

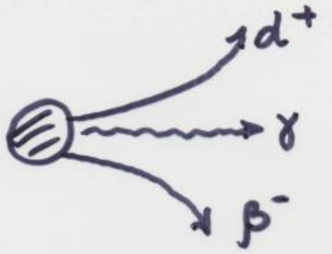
Riddles of β-ray spectra
(1899 - end of 20's y.)

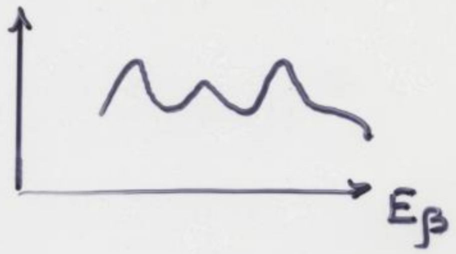
β-ray discovery, β-spectrometer	Becquerel, 1900 Paschen, 1904
Problem of absorbtion	
Exponential low	Schmidt, 06
new β-sources	Hahn, Meitner, 08
Linear low	Thomson, Bragg, Wilson, 09
Problem of β-lines	
β-lines spectrum (photoplates)	Danysz J., 11
(magnetic meth.)	Hahn, Meitner, 12
nulear origin of β	Bohr, 13
internal conversion γ into β	Rutherford, 14
experiments of β-lines of RaB+C	Rutherford, Robinson Rawlinson, 14
Continuous spectrum (Geiger count)	Chadwick, 14
Fine β-line spectra	Ellis, 20
β-α analogy	Meitner, 22
γ-spectra of nuclei	Smekal 22
Secondary electron effects, β-γ time order of emission	
Radiationless processes	Rosseland, 23
γ-ray absence in RaE	Meitner, 23
Primary of β-rays	Ellis-Skinner, 23 Ellis-Wooster, 25
Continuous spectrum riddle	
Heat measurements	Ellis-Wooster, 27
Upper limit in β-spectrum	Meitner, 29 Ellis, 29-32 Sargent, 32
Energy conservation in ThC - ThD β-chain cycle	Ellis, Nevil, 33

Riddles of β-rays

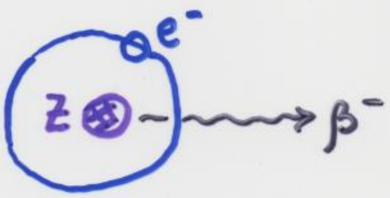
β-rays charge v, e/m, absorbtion	1900 -08	magnetic properties of β-rays	fast e^-
β-spectrometers photoplates, Geiger's counters	1910 -14	diff. spectra + monolines contin. spectrum	Atom. model of Bohr-Reserf. outer electrons
external source of β-lines excitations	1914	connect. of convers. lines with atomic electr.	photoeffect on outer e^-
β-line spectra, coordination with atomic ones	1920 -23	systematics of conv. lines γ-sp. from nuclei	coordin. with K, L, M ... atomic spectra, nuclear γ-rays
Z estimations from convers. lines β - γ order	1923 -25	priority of β absence of monoenerg. nucl. electrons	e-p nucl. model β-α analogy of L. Meitner
Investigation of RaE continuous spectrum, heat effect experim.	1927 -29	Problem of continuous spectrum $E_\beta \sim E_0/2$	Inner nucl. electrons? E conserv. law ?
Upper limit of β-sp. α-β chains in Th	1929 -33	β-sp. is nonstatistic? Energy conserv. law for $E_{0\beta}$	Quantum mech.? Paradox? Where is energy ?

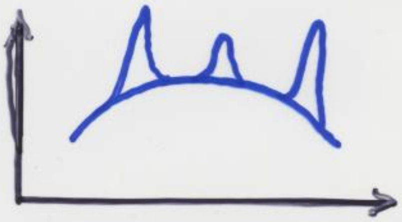
1900 - 08



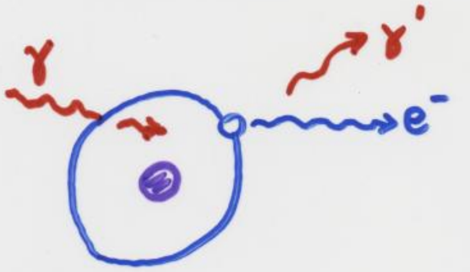


1910 - 14

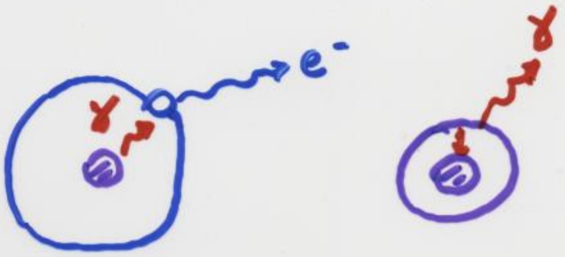


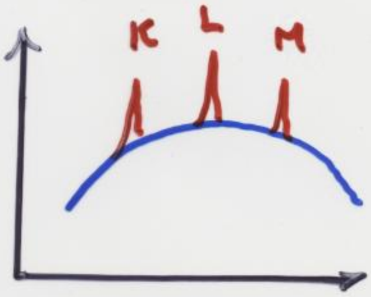


1914

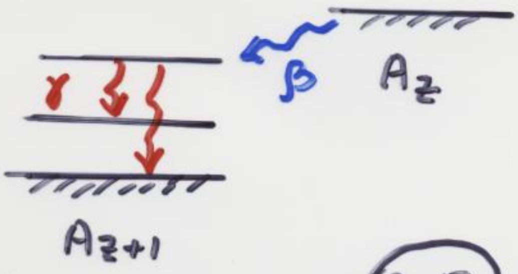


1920 - 23



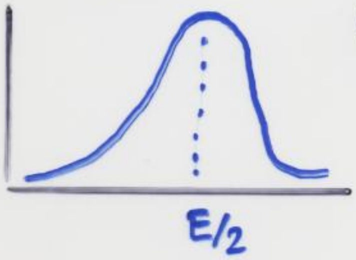


1923 - 25

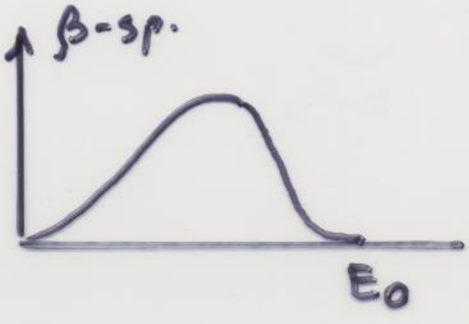


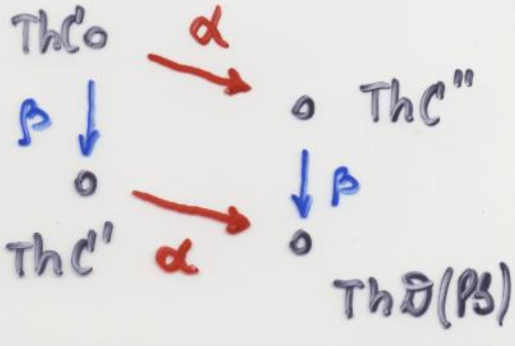
RaE

1927 - 29



1929 - 33





First experimental period (1899-20s)
(Radioact. families heavier Pb)

- β-particles are high-vel. electrons from nuclei (N. Bohr)
- Exper. β-spectra consist of β-lines + contin. β
- β-lines are result of internal conversion of nucl. γ-rays exited from atomic orbits (Rutherford)
- nuclei have excited states decayed through γ-rays β-rays preceeded nuclear γ.
- Contin. β-spectrum is of primary origin and γ-rays can be absent (RaE). It have the β-sp. upper limit.
- heat effect of β-rays shows its mean energy that is in contradiction with energy cons. law. However it can be restored if one uses in β-α chains the upper limits (ThC - ThD)
- nuclear structure is explained on p-e model base.

Thus it was formulated an experimental paradox - observed violation of energy conservation law.

Neutrino conception birth (1929 - 37)

Dirac equation	Dirac, 28
Weyl equation	Weyl, 29
Contradictions in nuclear p-e model (odd-odd nuclei)	Kronig, 28
Nonconservation of energy	Bohr, 29
"Neutron" Pauli hypothesis	Pauli, 30
Discovery of n	Chadwick, 32
Discovery of e^+	Anderson, 32
Proton-neutron nuclear model	Heisenberg, 32 Ivanenko, Majorana
β-decay theory with E-nonconserv.	Beck, Sitte, 33
Neutrino hypothesis	Pauli, 33
Fermi theory (in analogy with electrodynamics)	Fermi, 33
Proposal on ν mass estimation	Fermi, Perren, 33
Artificial radioactivity	Jolio, Curie, 34
Estimation of ν interaction $g \sim 4 \cdot 10^{-50} \cdot \text{erg sm}^3$	Bethe, Peierls, 34
Double β-decay	Heppert-Mayer, 35
Recoil effect measurm. in β-decay	Leipunsky, 35
Generalization of Fermi theory	Gamow - Teller, 36
Majorana neutrino	Majorana, 37
Konopinsky - Uhlenbeck scheem	Konopinskiy, Uhlenbeck, 35

Conclusions of 30's beginning

$H\psi = i\hbar\frac{\partial}{\partial t}\psi$ $\gamma_\mu \partial_\mu \phi + m\phi = 0$

Dirac

$m=0$ Weyl

P-nonconservation ?

$\boxed{p^+ e^-}$ $Li^6 = 6p^+ + 3e^-$

$\boxed{p\ n}$ $Li^6 = 3p^+ + 3n$

β-decay: $A(N,Z) \longrightarrow A(N-1, Z+1) + e^- + \nu$ Pauli

$H_{el.} = e^2(\bar{p}\gamma_\mu p)(\bar{e}\gamma_\mu e)\frac{1}{q^2}$

quant. electrodinamics

$e^2 = 1/137$

$H_\beta = G_F(\bar{p}\gamma_\mu n)(\bar{e}\gamma_\mu \nu)$

Fermi theory

$G_F m_e^2 \sim 10^{-10}$

Nondetectable neutrino!

$A(N,Z) \rightarrow A(N+1, Z-1) + e^+ + \nu$ β^+-decay

$e^- + A(N,Z) \rightarrow A(N+1, Z-1)$ K'-capture

$A(N,Z) \rightarrow A(N-2, Z+2) + 2e^- + 2\nu$ 2β-decay

$H_\beta = G_F(\bar{p}\,O_i\,n)(\bar{e}\,O_i\,\nu)$

$O_i = 1\ (S)\quad \gamma_\mu\ (V)\quad \sigma_{\mu\nu}\ (T)\quad i\gamma_\mu\gamma_5\ (A)\quad \gamma_5\ (PS)$

1937. Beginning of Majorana Physics.

Ettore Majorana

"Symmetric Theory of Electron and Positron."

Nuovo Cim. v. 14, 1937, p. 171 (Phys. P. a N. v. 34, 2003 p. 124)
(in Russian p. 239)

main items:

$$\left(\frac{\hat{W}}{c} + (\bar{\alpha}, \hat{\bar{p}}) + \beta mc\right) \psi(\bar{x}, t) = 0$$

$$\alpha_x = \rho_1 \sigma_x \, , \quad \alpha_y = \rho_1 \sigma_y \, , \quad \alpha_z = \rho_1 \sigma_z \, , \quad \beta = \rho_3 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

$$\downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow$$

$$\alpha_x \qquad \alpha_y^m = \rho_3 \qquad \alpha_z \qquad \beta^m = -\rho_1 \sigma_y = \begin{pmatrix} 0 & \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix} \\ \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix} & 0 \end{pmatrix}$$

major.
$$\left(\frac{1}{c}\frac{\partial}{\partial t} - (\underset{\text{real}}{\bar{\alpha}^m, \bar{\nabla}}) - i \underset{\text{real}}{\beta^m} \mu\right) \psi(x, t) = 0$$

$$\psi(\bar{x}, t) = U(\bar{x}, t) + i V(\bar{x}, t) = \mathrm{Re}\,\psi + i\, \mathrm{Im}\,\psi$$

$$\left(\frac{1}{c}\frac{\partial}{\partial t} - (\bar{\alpha}^m, \bar{\nabla}) + \beta'^m \mu\right) U(\bar{x}, t) = 0 \, , \quad \left(\frac{1}{c}\frac{\partial}{\partial t} - (\bar{\alpha}^m, \bar{\nabla}) + \beta'^m \mu\right) V(\bar{x}, t) = 0$$

Two independent equations for new particles (truly neutral)

C-transformation: $\psi^{(c)}(\bar{x}, t) = \rho_3 \psi^*(\bar{x}, t) = \pm \psi^*(\bar{x}, t)$

$U(\bar{x}, t)$: $\psi^*(\bar{x}, t) = \psi(\bar{x}, t) = \psi^{(c)}(\bar{x}, t)$

$i V(\bar{x}, t)$: $\psi^*(\bar{x}, t) = -\psi(\bar{x}, t) = \psi^{(c)}(\bar{x}, t)$

majorana conditions : $\psi^{(c)}(\bar{x}, t) = \pm \psi(\bar{x}, t)$

for neutral Particles : ν, n !

Here is the Beginning of Nonstandard
Neutrino Properties!

First theoretical period (1929-37)
(on quant.-mech. picture base)

- The fundament of quant.-mech. picture for atomic phenomena (Schredinger) was described

However:

- There was no nucl. phen. picture
- There was no relativistic phen. picture
  Dirac equation but no e^+
- There was no β-decay picture
- There was Weyl equation but with P-nonconserv.

- Two exits: Bohr's hypothesis on E-nonconserv on nuclear level
  Pauli's hypothesis on new, neutral particle

Experim. discoveries of e^+, n

Consequences: p-n nucl. model
relativ. quantum electrodynamics (QED)
neutrino Pauli hypoth.
Fermi β-decay theory in analogy with QED
Estimations of m_ν, G_F

Generalization of Fermi sch. to 5 variants
" " " by Konopinsky-Uhlenbeck

But Majorana hypoth. about neutr. particles $Q=0$

Thus, new particles were discovered and theory of weak processes was constructed, but
- what variant of theory?
- what is Weyl Eq. and major. hyp.?

neutrino in decay processes (30's - 50's years)

nuclear β-decay:

β^+ - decay	Curie, Jolio, 34
K - capture	Alvarez, 37
2β in majorana sch.	Furry, 39
neutron star collapse	Landau, 38
W - boson idea	Klein, 39
solar neutrino (pp cycle)	Bethe, 39

μ - meson decay:

meson theory of nucl. forces	(Tamm) Yukawa, 35
μ - discovery	Anderson, Nedemeyer, 38
μ - radioactivity	Rasetti, Rossi, 41

μ-decay mechanism:

No μ → eγ	Hincks, Pontecorvo, Sard Althaus, Piccioni, 48
3 - particle decay	Anderson, Steinberg, Hincks, Pontecorvo, Zhdanov
μ - e analogy	Pontecorvo, Klein 48
μ - decay parameters	michel' 50

Reactor neutrinous

First reactors	Fermi '42 Kurchatov '46
Reactor for neutrino search	Pontecorvo, Alvarez 46
n decay	Snell, Robson, Spivak 48
ν mass limit from T-decay	Curran, Hanna, Pontecorvo 49
ν registration	Reines, Cowan 53
Cl-Ar experiment ($\nu \neq \tilde{\nu}$)	Devis 56 - 59

neutrino from accelerators:

Pion flux	Gardner, Lattes '48
π → μν decay	Lattes, Occhialini, Powell '47
Strange particles in cosmic rays	Rochester, Batler '47
K^0 - duality, oscillations	Gell-mann, Pais, Piccioni, 53
K_2^0 - discovery	Lande 56

Summaries to middle 50's:

Neutrino of 40's years

$\textcircled{\nu}$ $m_\nu < 500\,eV$ (T) , $(\gamma_\mu p_\mu + m)\,\Phi_\nu = 0$

Dirac ν

β^- $A(N,Z) \to A(N-1, Z+1) + e^- + \nu$

β^+ $A(N,Z) \to A(N+1, Z-1) + e^+ + \nu$

K $A(N,Z) + e^- \to A(N+1, Z-1) + \nu$

$\pi \to \mu + \nu$, $\mu \to e + \nu + \nu$

$H_\beta = \underline{\underline{G_F}}\,[\bar p \gamma_\mu n](\bar e \gamma_\mu \nu) + h.c.$ (Fermi)

$H_\beta = \underline{\underline{G_F}} \sum_i [\bar p O_i n](\bar e O_i \nu)\cdot\lambda_i + h.c.$ (General form)

$O_i = 1\,(S)$, $\gamma_\mu\,(V)$, $\sigma_{\mu\nu}\,(T)$, $\gamma_\mu\gamma_5\,(A)$, $\gamma_5\,(PS)$

Experim. data : S + T

$(ft)_\beta$, $e\nu$-correl. , $\beta\gamma$-correl.

Allowed and forbid. β-transitions.

Problems: ν was not observed !

ν, $\tilde\nu$; or $\nu = \tilde\nu$?

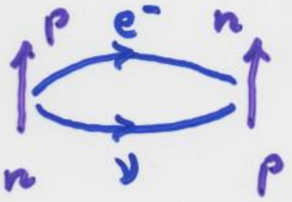
majorana ν what is it ?

Weyl equation

Road to π-meson!

N-N forces (1932)

Tamm's hypothesis (1935)



$\downarrow$

Yukawa's hypothesis (1935)

$m_\pi \sim 100$ MeV

Cosmic rays (1938) $\longrightarrow \mu^-$-showers

μ-radioactivity (1941) $\mu^- \to e^- +$ neutr. part.

No $\mu \to e\gamma$ (1948) $\mu^- \not\to e^- + \gamma$

3-decay of μ (1948) $\mu^- \to e^- + 2\nu$

μ - e - analogy

π- fluxes: $p + p \to p + n + \pi^+$ (1948)

π-decay: $\pi^\pm \to \mu^\pm + \nu$ (1947)

$\pi^\pm \to e^\pm + \nu$

1946 Inverse β Process . B. Pontecorvo.

NRC of Canada, DoAE, Chalk River
Report PD-205, 1946

... Direct proof of the existence of neutrino ... must be based on experiments, the interpretation of which does not require the law of conservation of energy, i.e. on experiments in which some characteristic process produced by free neutrinos (a process produced by neutrinos after they have been emitted in a disintegration) is observed.

$$\beta^- + Z \rightarrow \nu + (Z-1)$$

$$\nu + Z \rightarrow \beta^- + (Z-1) \quad , \quad \nu + Z \rightarrow \beta^+ + (Z-1)$$

$$\nu + Z + \beta^-(K) \rightarrow Z-1$$

$$\nu + Z \rightarrow \gamma + \beta^- + (Z+1) \quad , \quad \nu + Z \rightarrow \gamma + \beta^+ + (Z-1)$$

Consequently, the radioactivity of the produced nucleus may be looked for as a proof of the inverse process.

An Example:

$$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar \qquad !! \qquad \nu + {}^{79,81}Br \rightarrow \beta^- + {}^{79,81}Kr$$

$$^{37}Ar \rightarrow {}^{37}Cl \qquad\qquad {}^{79,81}Kr \rightarrow {}^{79,81}Br$$

(34 days, K-capture) (34h; emission of positrons of 0.4 MeV)

Cross sections

$$\sigma_{inv} \leq \lambda^2 \cdot \frac{\lambda}{c} \cdot \frac{1}{\tau} \qquad (\sim 10^{-42}\, cm^2 \quad E_\nu \approx 5\, MeV)$$

Sources.

"...The neutrino flux from the sun is of order of 10^{16} neutrinos $cm^{-2}s^{-2}$. The neutrinos emitted by the sun, however, are not very energetic. The use of high intensity piles permits two possible strong neutrino sources:

1. The neutrino source is the pile itself, during operation... The advantage of such an arrangement is the possibility of using high energy neutrinos emitted by all the very short period fission fragments. Probably this is the most convinient neutrino source.

2. The neutrino source is the "hot" uranium metal extracted from a pile, or the fission fragement concentrate from "hot" uranium metal...

In the case of the investigation of inverse β processes produced by electrons of γ rays of high energy, the best source is a betatron or a synchrotron..."

Chalk River Laboratory   November 13, 1946
Chalk River, Canada

It is the first Neutrino Programme.

Solar ν ↓

Reactor ν ↓

Accelarator ν ↓

1947 Nuclear Capture of Mesons and the Meson Decay

B. Pontecorvo, NRC of Canada, Chalk River, Ontario, Canad

Phys. Rev., 1947, v.72, p.246

The experiment of Conversi, Pancini and Piccioni [1] indicates that the probability of capture of a meson by nuclei is much smaller than would be expected on the basis of Yukawa theory...

? We notice that the probability (about $10^6 sec^{-1}$) of capture of a bound negative meson is of the order of the probability of ordinary K-capture processes, when allowance is made for the difference in the disintegration energy and the difference in the volumes of the K shell and of the meson orbit. We assume that this is significant and wish to discuss the possibility of a fundamental analogy between β processes and processes of emission or absorption of charge mesons... ?

In the hypothesis ... the process of nuclear absorbtion or production of a single meson would be accompanied by the emission of a neutrino.

June 21, 1947

[1] Conversi M., Pancini E., Piccioni O. // Phys. Rev., 1947, vol. 71, p. 209; see also Sigurgeirson T., Yamakawa A // Phys. Rev., 1947, vol. 71, p. 319

Thus:

$$\mu^- + A(N,Z) \longrightarrow \nu + A(N+1, Z-1)$$

$$\nu + A(N,Z) \longrightarrow \mu^- + A(N-1, Z+1)$$

1948 - 1950 B. Pontecorvo's articles

μ-e-decay

"The absorption of charged particles from the 2.2-microsecond meson decay." (with E.P. Hincks)

Phys. Rev., 1948, vol. 74, p. 697

"Search for gamma radiation in the 2.2-microsecond meson decay process" (with E.P. Hincks)

Phys. Rov., 1948, vol. 73, p. 257

"On the absence of photons among the decay products of the 2.2-microsecond meson" (with E.P. Hincks)

Phys. Rev., 1950, vol. 28 A, p. 29

"On the disintegration products of the 2.2-microsecond meson." (with E.P. Hincks)

Phys. Rev., 1950, vol. 77 p. 102

$\mu \to e + \nu + \nu$; $\mu \to e + \gamma$ (No!)

β-decay "The neutrino and the recoil of nuclei in beta disintegration" Reports on Progress in Physics London: The Physical Society, 1948, vol. 11, p. 32

"The β spectrum of ^3H" (with G.C. Hanna)
Phys. Rev., 1949, vol. 75, p. 983 $m_\nu < 500 eV$?

"Recent developments in proportional counter technique"
Helv. Phys. Acta, 1950, vol. 23, Suppl. 3 p. 97-118

Second experimental period (30's - 50's)
(wide investigations of decay processes)

- Nucl. physics was developed, new classes of β-processes were observed: β^+, K-capture 2β (th.), neutron β-decay

- New particles were discovered - mesons: π, K, K^0, W-exch. meson hypoth., K^0-oscill.

- μ-meson and its radioactivity was observed 3-part. decay with 2 neutrino participation

- New astrophysical concepts:
  - star neutron collapse
  - p-p cicle in Sun

- Reactors as ν-sources $\nu + p \to n + e^+$

- ν experiments became reality:
  - m_ν estimation from T-decay
  - Registration ν from reactor
  - ν flux from accelerators
  - $\sigma_\nu \sim E_\nu^2$

Thus neutrino became a real object for physical investigations!

Neutrino theory and Standard model Birth.
(1953 - 1967)

Lepton charge	Marx, Zeldovich, Konopinski-Mahmoud 53
Yang-Mills fields	Yang, Mills, 54
CPT-theorem	Lüders, Pauli, 54
CVC-hypothesis	Gershtein, Zeldovich, 55
P-nonconservation in weak processes	Lee, Yang 56 (Shapiro 55)
in β-decay	Wu, 57
in μ, π -decays	Garvin, Lederman, Weinrich Freidman, Telegdi, 57
CP-conservation	Landau, Lee, Yang, 57
2-component neurtino	Landau, Salam, Sakurai, 57
Universal V-A inter.	Gell-Mann, Feynman Sudarshan, Marshak, 57
ν-oscillation hypothesis	Pontecorvo, 57
PCAC hypothesis	Goldberger, Treiman 58
SU(3) symmetry	Gell-Mann, Levi, Okun' Kobzarev 58-63
Cabibo angle	Cabibo 63
CP-violation	Christenson, Cronin, Fitch, 64 Turlay

Forming of Standard Model

Electroweak interaction	Schwinger, 57
Calibration theory = gauge theory	Glashow, 61
Higgs mechanism	Higgs, 64
Nonintegral quark charges	Gell-Mann, Zweig, 64
Standard model	Glashow, Salam, Weinberg 61-67
SM renormalizability	t'Hooft, 71

Weak interaction in atoms	Zeldovich, Khriplovich 59
Weak NN interaction	Blin-Stoyle, Shapiro, Lovashev, 66 Abov, 64

1957 Pontecorvo returns to neutrino physics

(after T.D.Lee - C.N. Yang, 1957)

"Some remarks on slow processes of transformation of elementary particles" (with L.B.Okun)

Zh. Eksp. Teor. Fiz., 1957, vol. 32, p. 1587

Discussion on nonlepton weak processes and estimations of $K^0_0 \to \tilde{K}_0$ process by using $|\Delta S| = 2$ mechanism

"Mesonium and antimesonium"

Zh. Eksp. Teor. Fiz., 1957, vol. 33, p. 549

"Gell-Mann and Pais [1] first pointed out the interesting consequence of the fact that K^0 and $\tilde{K}^0$ particles are not identical [2]. The possibility of $K^0 \to \tilde{K}^0$ transitions induced by weak interactions makes it necessary to consider neutral K^0 meson as a mixture of particles of different (combined) [3] parity (K_1^0 and K_2^0).

We discuss here the problem as to whether there exist other "mixed" neutral particles (not necessary "elementary" ones) which are not identical to the corresponding antiparticles and for which particle ⇄ antiparticle transitions are not strictly forbidden.

... by conservation laws for the number of barions and light fermions (... nuclear [4] and neutrino [5] charges).

$$(\mu^+ e^-) \longrightarrow (\nu + \tilde{\nu}) \longrightarrow (\mu^- e^+)$$

... The law of conservation of neutrino charge is not yet definitely established: it is only established experimentally that neutrino and antineutrino are not identical particles [8]. If the theory of two component neutrino [9] was not valid ... and if the conservation law for neutrino charge took no place, neutrino → antineutrino oscillation in vacuum would be in principle possible...

1957 B.Pontecorvo's hypothesis on neutrino oscillation.

"Inverse β-processes and non-conservation of lepton charge."

JINR Preprint P-95, Dubna, 1957

"Not long ago the question was raised [1] as to whether there exist neutral particle mixtures, other than K^0 mesons [2], ... for which the transition particle → antiparticle is not strictly forbidden...
It was noted that neutrino may be such a particle mixture and consequently that there is a possibility of real transitions neutrino → antineutrino in vacuum, provided that the lepton (neutrino) charge [3] is not conserved...

Recently there came to our attention a paper by Davis [4], who investigated the production of ^{37}Ar from ^{37}Cl ... Below it is assumed that a) the neutrino (ν) and antineutrino ($\tilde{\nu}$) emitted in the processes

$$p \rightarrow n + \beta^+ + \nu \quad , \qquad n \rightarrow p + \beta^- + \tilde{\nu}$$

are not identical particles; b) the neutrino charge is not strictly conserved...

$$p \rightarrow n + \beta^+ + \tilde{\nu} \quad , \qquad n \rightarrow p + \beta^- + \nu$$

are possible, although ... they are less probable...

It follows from a) and b) that neutrinos in vacuum can transform themselves into antineutrino and vice versa. This means that neutrino and antineutrino are particle mixtures, i.e. symmetrical and antisymmetrial combination of two truly neutral Majorana particles ν_1 and ν_2 having different combined parity [5]...
... So, for example, a beam of neutral leptons from a reactor which at first consist mainly of antineutrinos will change in composition and at a certain distance R from the reactor will be composed of neutrino and antineutrino in equal quantities...

... The upper limit of R which can give observable effects in the experiment of Cowan and Rines [6] is of order of a meter, which corresponds to a time for the transformation neutrino → antineutrino $T \leq 10^{-8}$ sec. If one takes into account that the neutrino energy ... is always larger by several orders of magnitude than $m_\nu c^2$ ... and that ... in laboratory system there is a considerable relativistic increase of the transformation time then the question arises as to whether the condition $T \leq 10^{-8}$ sec is plausible ... The time T is [9] about $10^{-10} \times \frac{\text{neutrino energy}}{m_\nu c^2}$ sec which is considerably grater than 10^{-8} sec...

(!)... In conclusion it is interesting to underline that, independently of the plausibility of the concrete effects which were discussed above, non-conservation of neutrino charge under the condition that neutrino and antineutrino are distinguishable entities (or which is the same, the existence of two Majorana neutrinos with different combined particles) inevitably leads to effects of Gell-Mann - Pais - Piccioni type [2]. Under the above assumptions, effects of transformation of neutrino into antineutrino and vice versa may be unobservable in the laboratory because of large values of R, but will certainly occur, at least, on an astronomical scale... (!)

1957. B. Pontecorvo.

It is interesting to compare Pontecorvo's estimation with modern data:

$$L \sim 10^{-10} \frac{E_\nu}{m_\nu c^2} \text{sec} \cdot 10^{10} \frac{\text{cm}}{\text{sec}} \sim \frac{E_\nu(\text{MeV}) \cdot 10^6}{10^{-2}\text{eV}} \text{cm} \sim 10^8 \text{cm} \sim \underline{10^3} \text{ km} \; !$$

$$\text{for } \underline{E_\nu \sim 1 \text{ MeV}}$$

modern Experiment $L \sim 10^2$ km

1962 Neutrino mixing in Sakata models

1. "Possible unified models of elementary particles with two neutrinos"
   T. Katayama, K. Matumoto, S. Tanaka, E. Yamada
   Prog. Theor. Phys. v. 28, 1962, p. 675

2. "Remarks on the unified model of elementary particles."
   Z. Maki, M. Nakayama and S. Sakata
   Prog. Theor. Phys. v. 28, 1962, p. 870

Sakata - Nagoya model : p, n, Λ SU(3) hadron symmetry
(Sakata, 1956)

Gamba - Marshak - Okubo : ν, e, μ lepton-hadron symmetry
(1959)

$$\Big\downarrow B^+\text{-matter}$$

$$p = (B^+\nu) \quad , \quad n = (B^+e^-) \quad , \quad \Lambda = (B^+\mu^-)$$

Cabibo mixing: $J_h(x) = (\bar{n}p) + c(\bar{\Lambda}p) \rightarrow \cos\theta_c(\bar{n}p) + \sin\theta_c(\bar{\Lambda}p)$

$$G_\mu^2 = G_n^2 + G_\Lambda^2 \qquad n' = \cos\theta_c\, n + \sin\theta_c\, \Lambda$$

Discovery of two neutrinos - ν_μ, ν_e (1962)

modification: $\nu_1 = \nu_e \cos\delta + \nu_\mu \sin\delta$, $\nu_2 = -\nu_e \sin\delta + \nu_\mu \cos\delta$

$$p = \langle B^+\nu_1\rangle \quad , \quad n = (B^+e^-) \quad , \quad \Lambda = \langle B^+\mu^-\rangle \quad , \quad (B^+\nu) - \text{No!}$$

$$\nu_e = \nu_1 \cos\delta - \nu_2 \sin\delta \quad , \quad \nu_\mu = \nu_1 \sin\delta + \nu_2 \cos\delta$$

..."However, weak neutrinos are not stable due to the occurance of virtual transformation $\nu_e \leftrightarrow \nu_\mu$ ..."

In 1. two majorana neutrino case was also mentioned!

Thus: Hadron - Lepton Sym. Cabbibo angle hypothesis

Two ν experiment ($\nu_{e,\mu}$) ⟶ neutrino mixing hypothesis !

Second theoretical period (1953-67): discovery of parity nonconservation and Standard Model construction.

- There are divergant problem in QED
- Concepts of discrete operations (P, T, C) and lepton charge in opposite to Q are developed
- In K-decays θ-τ problem appeared that lead to nonconserv. parity hypothesis

- Experimental discov. of P-violation:
    - in nuclear β-processes
    - in particle decays: μ, π, K ...
  - hypothesa of weak inter. in nuclei (NN) atoms (Ne) appeared

Theory returns to Weyl and Fermi:
- 2 component neutrino
- CP-conservation
- V-A univ. interaction
- CVC, PCAC hypothesa

CP-violation experim. discovery

SM is formulated: EW interaction, calibr. theory = gauge Higgs' mech, SU(3) quark scheem, gluons, renormaris!

However, Pontecorvo neutrino oscill. hypothesis in analogy with K^0-osc. appeared
(then 2-flavour osc. version)

Beginning of experimental neutrino physics, Statement of Standard Model (60's-70's)

ν in nuclei (ν_e)

ν polarization	Goldhaber '58
$\nu_e \neq \tilde{\nu}_e$	Davis '59
Prop. on neutr. curr. (D, Li)	Gaponov, Gershtein '62
Geochemical exp. on 2β	64
m_ν from T-decay (< 35eV)	Tretyakov et al. 76
$\nu_e e$ in reactor ν flux	Reines et al. 76
$\nu_e D$ in reactor ν flux	Reines et al. 79

ν from accelerator (ν_μ)

$\nu_\mu \neq \nu_e$	Danby et al. '62
magnetic furnace for ν fluxes	Van der Meer '63
ν in bubble chamber	Bloch '63
$\nu_\mu \neq \tilde{\nu}_\mu$	Bernardini '64
Parton model	Bjorken, Pasches, Feynman '69
$\nu_\mu e$	Hasert et al. '73
$\nu_\mu N$ (neutr. curr.)	Hasert et al. '73
J/ψ (c-quark)	Ting, Rihter et al. '74
Υ (b-quark)	Herb et al. '77
τ-meson	Perl et al. '75
W, Z - bosons discovery	CERN '84

ν in astrophysics

Hot Universe	Gamow '46
Solar neutrino	Fauler '58
Underground experim.	Markov, Greison '60
ν sea in Universe	Pontecorvo, Smorodinsky '61
First undergr. detector (~8700 m w.e.)	Reines '63
ν processes in stars	Fauler, Hoyle '65
in n collapse	Zeldovich '65
Relict γ radiation	Penzias, Wilson '65
Hyp. relict ν	Bick, Zeldovich, Novikov
Theory sol. ν experim	Bahcall '72
ν Baksan telescope	Chudakov '77
Solar ν registration (10 years)	Davis '78

Summary up to 80's : ν fluxes and ν detectors

Neutrino of 60's

ν_e , $\tilde{\nu}_e$; ν_μ , $\tilde{\nu}_\mu$ - two types of ν.

$(\gamma_\mu p_\mu)\Phi_\nu = 0$ Weyl equation

$\beta^\pm$-decay , K-capture , 2β-decay (estimations)

π, K - decays , $\mu^- \to e^- + \tilde{\nu}_e + \nu_\mu$

Universal weak interaction!

$$H_W = \frac{G_F}{\sqrt{2}} J_\mu^+ J_\mu \qquad J_\mu^h = (\bar{p}\gamma_\mu(1-\lambda\gamma_5)n)$$

$$J_\mu^l = (\bar{e}\gamma_\mu(1+\gamma_5)\nu)$$

G_β , G_S , $G_\mu^2 = G_\beta^2 + G_S^2$ - empirical rule.

$\shortparallel$ $\shortparallel$

$G_\mu \cos\theta_c$, $G_\mu \sin\theta_c$

Experim. data : $V - \lambda A$, $\lambda \approx 1.25$

$(ft)_{0-0}$, $(ft)_{n,GT}$, $(e\nu)$, $(\bar{J}e)$,

$(\bar{J}\nu)$, $\bar{J}[\bar{e} \times \bar{\nu}]$, $\beta\gamma_{circ.}$-corr. , $\pi \to \mu\nu_\mu$

ν-fluxes : $\tilde{\nu}_e$, ν_μ

Neutral curr: $\nu + e \to \nu' + e'$, $\nu + N \to \nu' + N'$?

NN-weak int. , Ne-weak inter.

Problems: Neutral currents ?

Majorana ν ?

Weak Interaction Hamiltonian
(Modern data)

Yu. Gaponov, Ya.F. (2000)

General Theory:

$$H_\beta = (G_{F\beta}/\sqrt{2}) \sum_i{}' (\bar{\Psi}_p O_i \Psi_n)\ (\bar{\Psi}_e O^i (C_i + C_i' \gamma_5) \Psi_{\nu e})$$

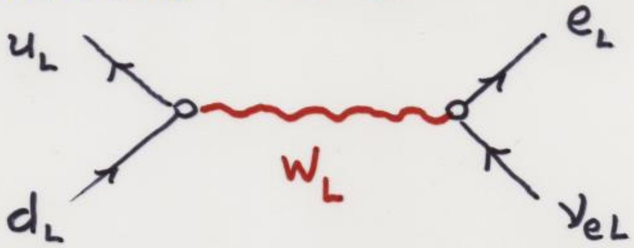
It includes 15 parameters (8 real ones) due to

$O_i = 1$ (S), γ_μ (V), $\sigma_{\mu\nu} = 1/(2i)(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$ (T), $i\gamma_\mu \gamma_5$ (A)

contributions

Theor. Hypotheses:

1. CP - conservation → 8
2. V, A - currents (W_L - Boson) → 4
3. L - neutrino → 2



Standard Model:

$$H_{SM} = (G_{V\beta}/\sqrt{2})(\bar{\Psi}_p \gamma_\mu (1 - \lambda \gamma_5) \Psi_n)(\bar{\Psi}_e \gamma^\mu (1 + \gamma_5) \Psi_{\nu e})$$

$$G_{V\beta} = 1.4183(18) \cdot 10^{-62}\ \mathrm{J\,m^3}$$

$$\lambda = -1.2673(10)$$

Neutron experiments

n-decay probab: $dW(E_e, Z, \Omega_e, \Omega_\nu) =$

$$G^2_{F\beta}/(2\pi)^5\, F(\pm Z, E_e)\,(E_e - E_{e0})^2\, E_e\, p_e\, dE_e\, d\Omega_e\, d\Omega_\nu$$

$$(1 + (b\, m_e/E_e)\sqrt{1-\alpha Z^2} + a(\bar p_e \bar p_\nu)/E_e E_\nu + A(\bar J \bar p_e)/E_e + B(\bar J \bar p_\nu)/E_\nu$$

$$+ D(\vec J[\bar p_e \times \bar p_\nu])/E_e E_\nu + \underbrace{E(\vec J[\bar\sigma_e \times \bar p_\nu])/E_\nu}_{\substack{\| \\ R\text{-param.}}}$$

$b = 0$ Fierz terms absence

Realized Experiments:

$(f\tau)_n$	n life-time
a	$e\nu$-correlation
A	eJ_n-correlation
B	νJ_n-correlation
D	triple $e\nu J$-correlation

Non realized Experiments:

$\vec\sigma_e$	e-polar. measur. (or $\vec P_\gamma$ - γ-polar.)
$\vec\sigma_p$	p-polar. measur.
$E(R)$	triple correl.

0^+-0^+ nucl. transitions:

$$(ft)_{0-0}(1+\delta_R)(1-\delta_c) = (Ft)_{0-0} = K\ln 2/2G^2_{V\,0-0}$$

$$G_{V\,0-0} = 1.4173(11)\cdot 10^{-62}\ \mathrm{J\,m^3}$$

n decay in Standard model

$f_n\tau_n = K'/(G_{V\beta}^2(1+3\lambda^2))$ $f_n = 1.71465(14)$

89 (2)

$A = -2(\lambda+\lambda^2)/(1+3\lambda^2)$

$B = -2(\lambda-\lambda^2)/(1+3\lambda^2)$

$a = (1-\lambda^2)/(1+3\lambda^2)$

(τ_n) $\tau_n = 885.7(10)$ s

From 0-0 ; τ_n data $\lambda = -1.2675(10)$

(A) $\bar{A} = -0.1161(7)$

From A data $\lambda = -1.2664(19)$

Exp. discr.

(B) Old: $B = +0.9820(40)$

New: $(A-B)/(A+B) = -1.2686(49) = \lambda$

$B = +0.9876(4)$ in SM

(a) $a = -0.1017(51)$

From a data $\lambda = -1.2591(168)$

Mean value $\lambda = -1.2673(9)$

Third experimental period (60's - 70's)
ν physics development and SM statement.

3 main directions in ν physics:

Low energy neutrino (β-decay and reactor ν)

- ν properties - m_ν, P_ν
- approvement of $\nu_e \neq \tilde{\nu}_e$
- investigation of $\nu_e D$, $\nu_e e$ processes

Extreemal low cross sections!

High energy neutrino (accelerators)

- new methods of ν registration (Buble ch.)
- approvement of $\nu_e \neq \nu_\mu$, $\nu_\mu \neq \tilde{\nu}_\mu$, ν_τ from τ-decay
  3 fam. of ν
- investigations of $\nu_\mu N$, $\nu_\mu e$ processes
- new quarks discoveries - c, b, t

SM experim. approvement

- neutral processes
- W, Z - bosons

Neutrino astrophysics:

ν - Solar, Star, Collapse, ν-sea
Solar ν experiments - first plans and Experim.
Underground Labs, ν-telescopes

Thus, our knowledges on ν properties widen up to ν-scattering, ν was investigated in SM frames and is now a new instrument.
ν fluxes, ν detectors appeared.
Special role ν in Universe was discovered.

Standard model (GSW - theory)

1. Leptons: Massless ⟶ Massive

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \qquad m_\nu - ?$$

$$(e)_R \qquad (\mu)_R \qquad (\tau)_R$$

2. Quarks: Massless ⟶ Massive

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad m_q - ?$$

$$(u)_R \qquad (c)_R \qquad (t)_R$$

$$(d)_R \qquad (s)_R \qquad (b)_R$$

3. Quark mixing:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \text{Kobayashi} \\ \text{Masakawe} \\ \text{Matrix} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \left(\begin{matrix} d\cos\theta_c + s\sin\theta_c + \dots \\ -d\sin\theta_c + s\cos\theta_c + \dots \\ \dots \end{matrix} \right.$$

Neutrino mixing - ?

4. Gauge fields:

$\gamma, Z^0, W^\pm$; $G_{\alpha\beta}$ (8 colour pairs)

Weak + EM int → γ, Z^0 , Inter. constants

$\nu\gamma$-int. = 0 $\qquad g, g'$; $\sin\theta_W$

5. Higgs boson + spont. broken vacuum

Constr. mass mechanism ?

6. Fundamental symmetry:

$$SU(3) \times \underbrace{SU(2) \times U(1)}_{\text{electroweak}}$$

In search for an exit beyond Standard model Theory (80's years)

Modern conception of the Standard Model

Theories of Grand Unification

Unification of interactions: EM, Weak, Strong, Gravity...
Left - Right Handed scheems
Lepto - Quark scheems
Supersymmetrical theories
Superstrings

nonstandard neutrino propertíes

majorana models
$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ oscillations
neutrino oscillation in matter (MSW-mech.)
neutrino anomal magnetic moment
neutrino precession (VVO-mech.)
neutrino flavor precession (LMA-mech.)

Astrophysics and cosmology

Solar neutrino
neutrino from collapsed stars
Origin of elements in star bursts
Dark matter in the Universe

MSW - Mikheev, Smirnov, Wolfenstain

VVO - Voloshin, Vysotsky, Okun

LMA - Lim, Marsiano, Akhmedov

Experiment in search for exit beyond the Standard model (80-90's years)

Supernova SN-1987A

Reactor ν

νp , νe , νD -experiments

ν magnetic moment

ν_e-oscillations

ν-diagnostics

Solar ν

Cl-Ar, Kamiokande

$\nu_\odot$-deficit !

SAGE - GALLEX

Super-Kamiokande

SNO ! $\nu_e + \nu_{\mu,\tau}$ 2001

Borexino etc.

Accelation ν

High E_ν

LSND !

Measurement on great distance

ν from Earth

Atmospheric ν

$\nu_\mu \leftrightarrow \nu_\tau$ oscillations (98-99) !

β-decay

Right-handed currents

Lepto-quark Bosons

CP-violation

ν mass from T

2β decay

2β (0ν)-decay from gramm to tons

Search for dark matter

Solar neutrino physics

Standard solar model

Radius	696 000 km
Surface T°	5773 °K
Central T°	$15.6 \cdot 10^6$ °K
Contents of H	34.1 %
Contents of He	63.9 %
Rest elements	1.96 %
Central density	148 g/sm^3

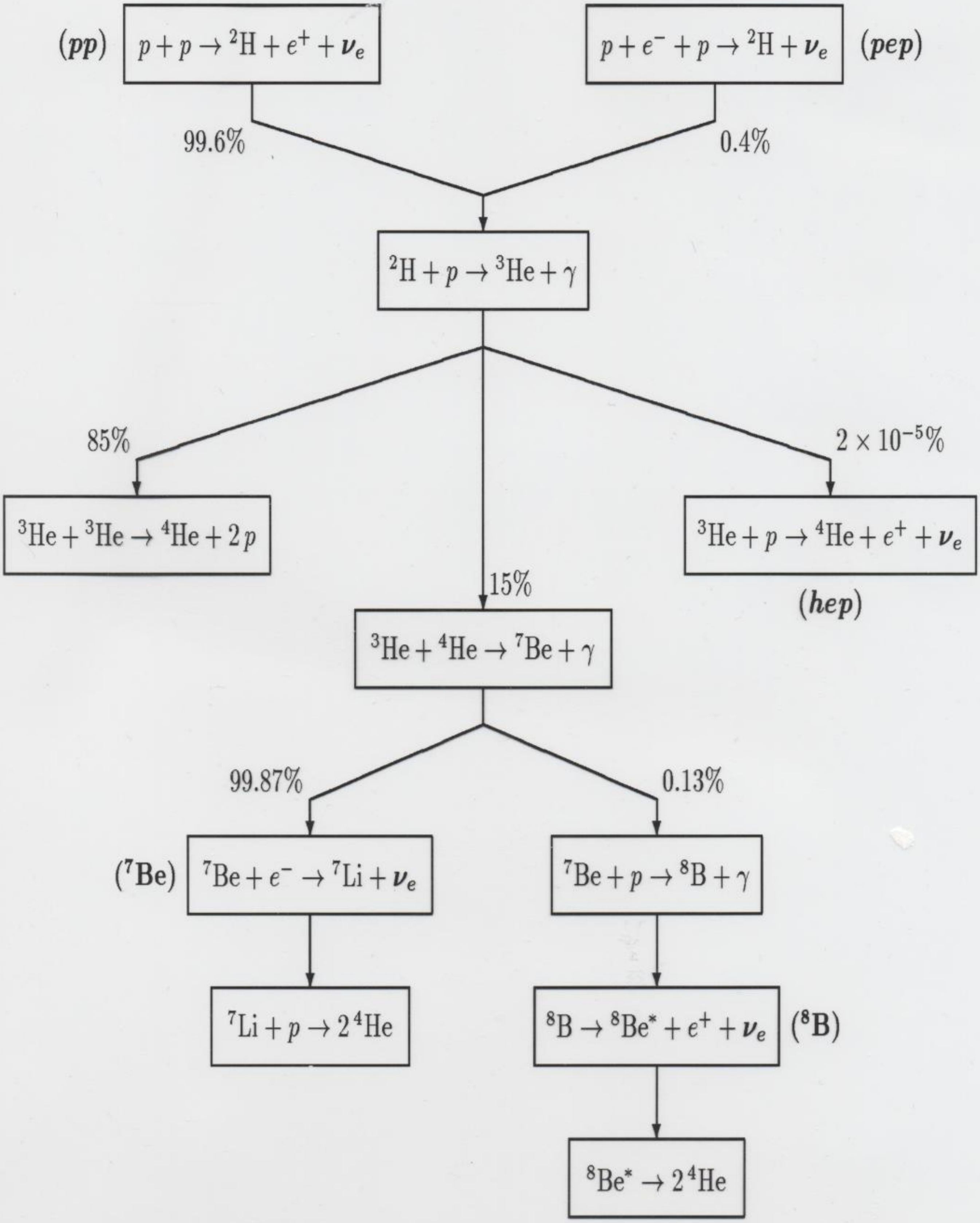
Neutrino fluxes on the Earth

Source	Reaction	E(MeV)	$\Phi (sm^{-2} s^{-1})$
pp	$pp \to De^+\nu_e$	$0.27 \div 0.42$	$5.94 \cdot 10^{10}$
pep	$pep \to D\nu_e$	1.445	$1.4 \cdot 10^8$
$^7\beta e$	$e\,^7\beta e \to {}^7Li\,\nu_e$	0.385 0.865	$4.8 \cdot 10^9$
$^8\beta$	$^8\beta \to {}^8\beta e^* e^+ \nu_e$	$6.73 \to 15$	$5.15 \cdot 10^6$

ν-oscill. mechanism hypothesa

Resonance	MSW
Precession of μ_ν	VVO
spin-flavor precession	LMA

SSM - pp cycle



(**pp**) $p + p \rightarrow {}^2\mathrm{H} + e^+ + \boldsymbol{\nu}_e$

$p + e^- + p \rightarrow {}^2\mathrm{H} + \boldsymbol{\nu}_e$ (**pep**)

99.6%

0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

$2 \times 10^{-5}\%$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\,p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \boldsymbol{\nu}_e$

(**hep**)

15%

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

99.87%

0.13%

(**^{7}Be**) ${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \boldsymbol{\nu}_e$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

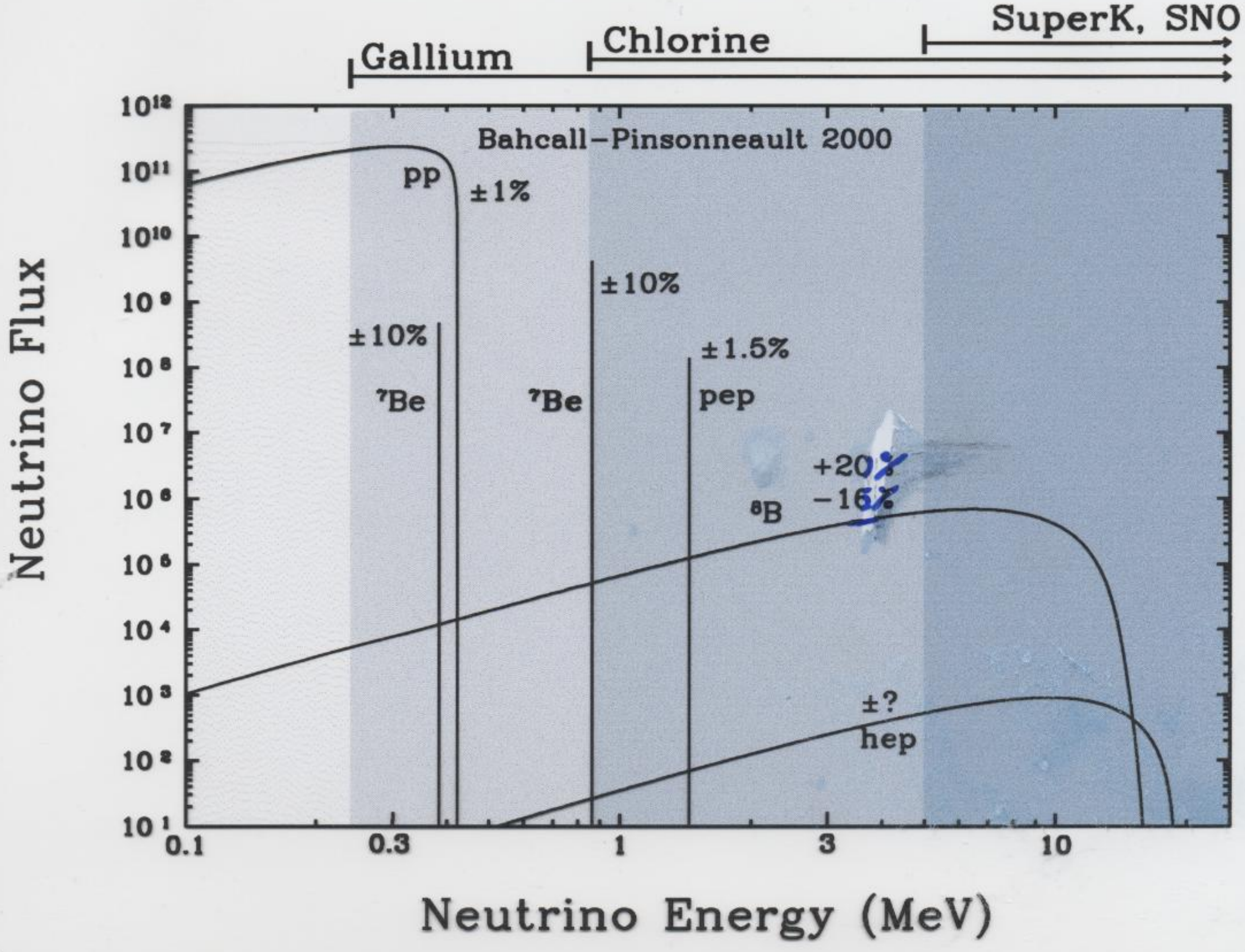
${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \boldsymbol{\nu}_e$ (**^{8}B**)

${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

SSM - neutrinos

Source	Reaction	$E_\nu^{Av.}(MeV)$	$E_\nu^{Max.}(MeV)$
pp	$p+p \to d+e^+ + \nu_e$	0.2668	0.423
pep	$p+e^- +p \to d+\nu_e$	1.445	1.445
^{7}Be	$e^- + {}^7\mathrm{Be} \to {}^7\mathrm{Li} + \nu_e$	0.3855	0.3855
		0.8631	0.8631
^{8}B	$^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$	6.735	~ 15
hep	$^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$	9.628	18.778
^{13}N	$^{13}\mathrm{N} \to {}^{13}\mathrm{C} + e^+ + \nu_e$	0.7063	1.1982
^{15}O	$^{15}\mathrm{O} \to {}^{15}\mathrm{N} + e^+ + \nu_e$	0.9964	1.7317
^{17}F	$^{17}\mathrm{F} \to {}^{17}\mathrm{O} + e^+ + \nu_e$	0.9977	1.7364



Solar neutrino detectors of first generation.

1 SNU = 1/10^{36} event/s

1. Chlorine Argon method (B. Pontecorvo, 1946)

$$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar^* + e^-$$

$$\xrightarrow[\text{35 days}]{\text{K-capt.}} e^- + {}^{37}Ar \rightarrow {}^{37}Cl$$

Homestake. R. Devis et al. 4100 m.w.e.

610 t C_2Cl_4 ${}^{37}Cl$ (24%)

2. Gallium Germanium method (V. Kuzmin, 1966)

$$\nu_e + {}^{71}Ga \longrightarrow {}^{71}Ge^* + e^-$$

$$\xrightarrow[\text{11.4 days}]{\text{K-capt.}} e^- + {}^{71}Ge \rightarrow {}^{71}Ga$$

SAGE. G. Zatsepin, V. Gavrin et al. 4700 m.w.e.

60 t natur. Ga ${}^{71}Ga$ (39.9%) ${}^{51}Cr$ (513 gr)

Effect. 0.95(12) 0.5 MCi

GALLEX Italy-Germ. Coll. Gran-Sasso 3400 m.w.e.

30 t $GaCl_3$ (120) Effect. 0.92(8) ${}^{51}Cr$ (1.7 MCi)

↓

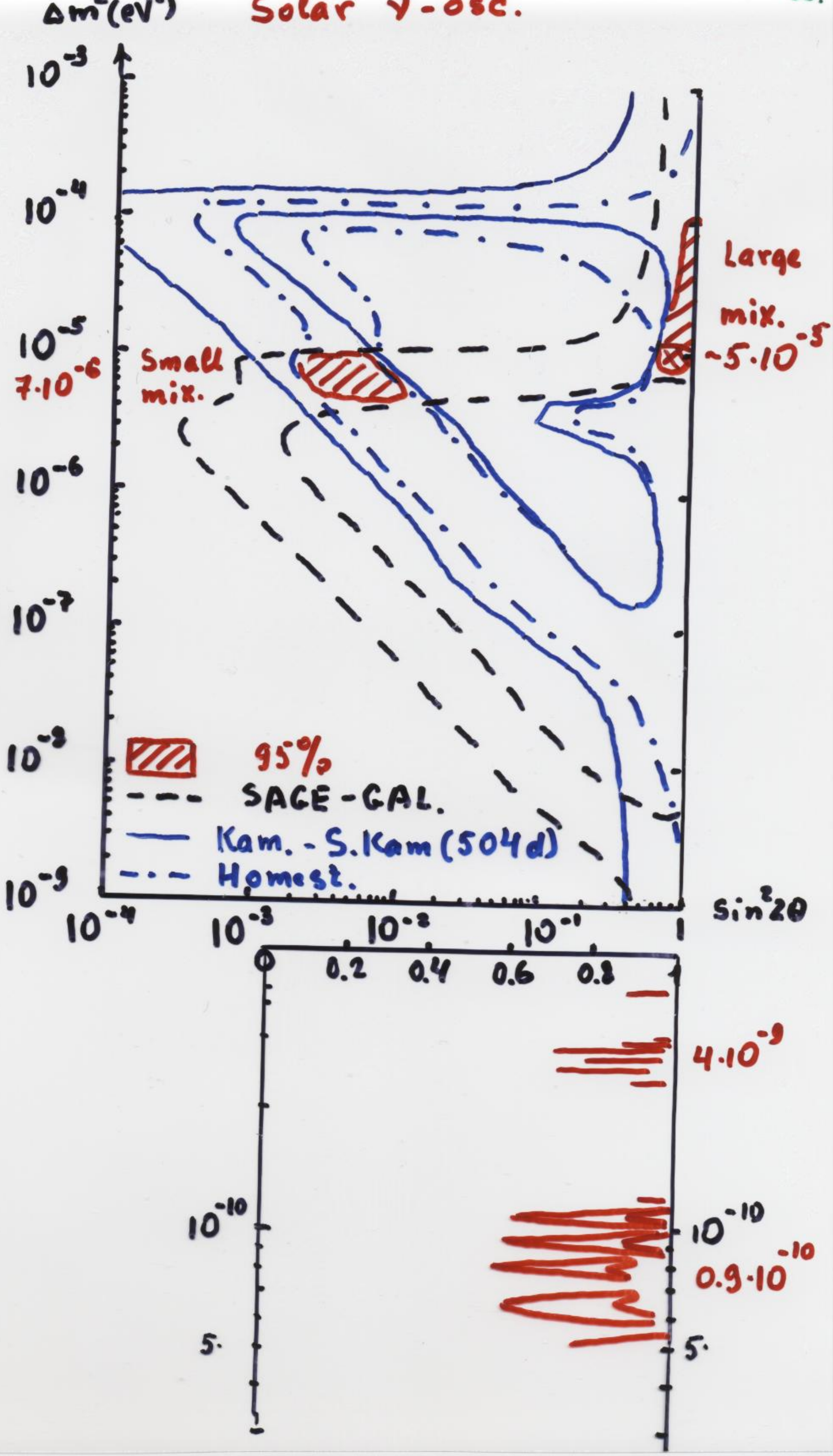
GNO Gran-Sasso

3. Kamiokande, Super Kamiokande

$$\nu_e + e^- \longrightarrow \nu_e' + e' \qquad (> 6.5\ \text{MeV})$$

SK 50000 t H_2O (32000 t) 11000 PhM

Solar ν-osc.

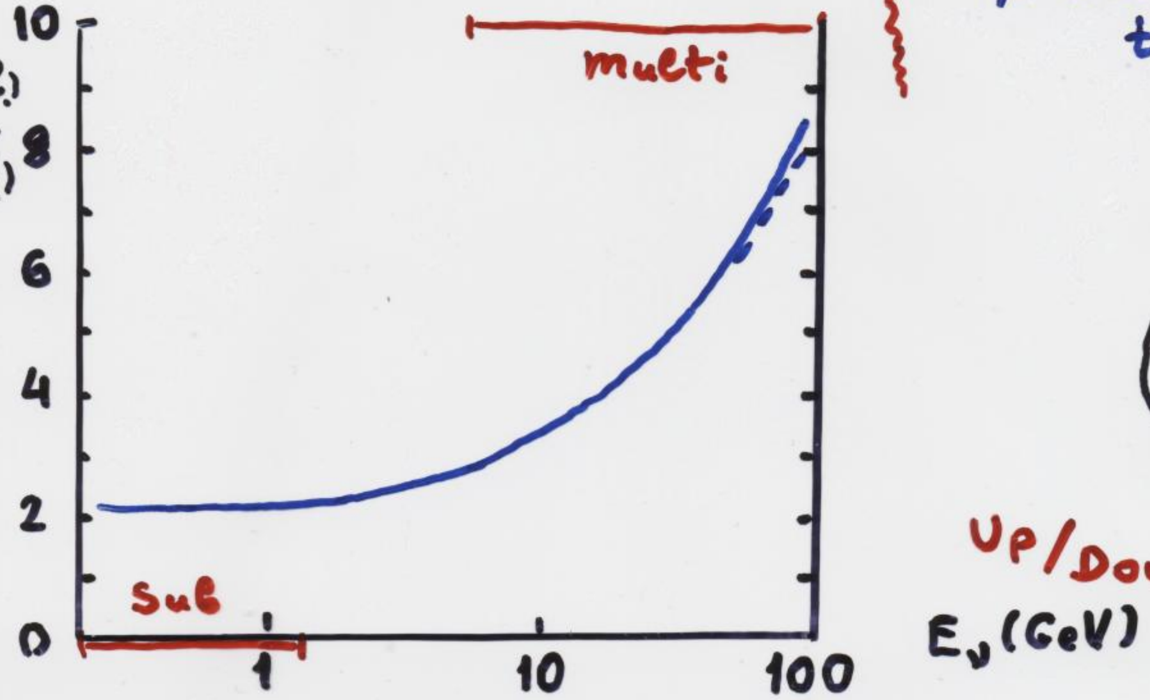


MSW

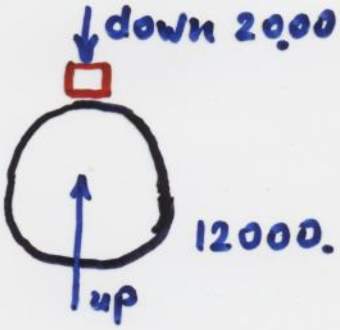
H.-Lang.

Atmospheric ν

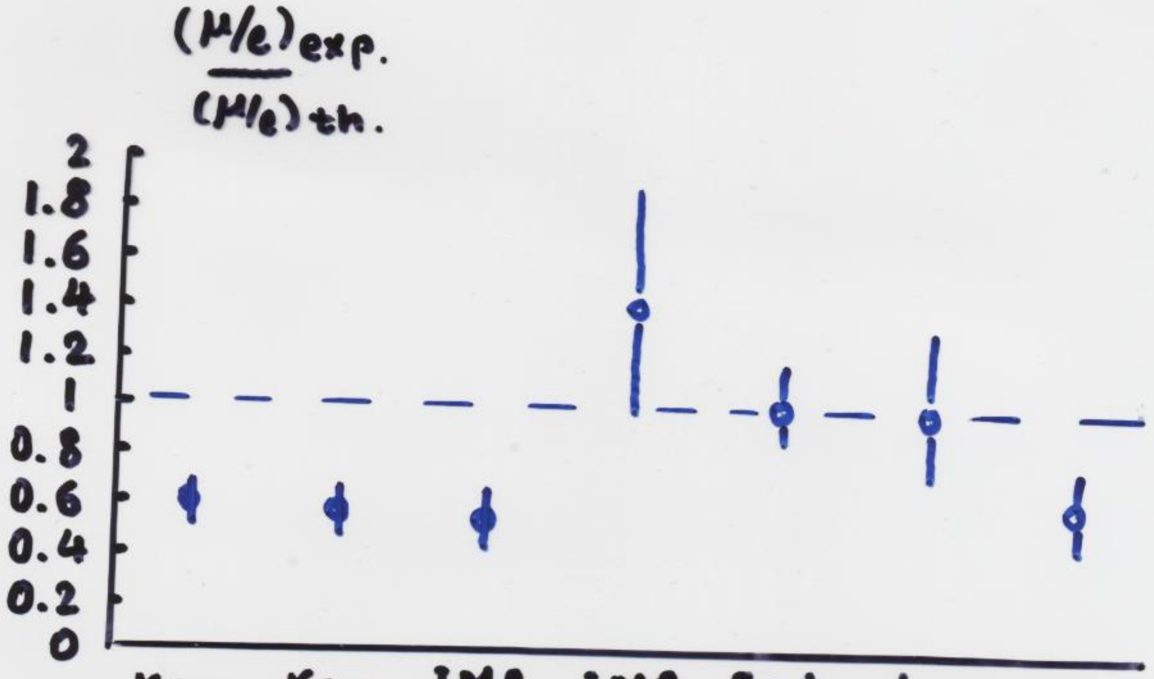
$$p, He \longrightarrow \pi\, \underset{\downarrow}{\nu_\mu} \longrightarrow \mu\, \underset{\downarrow}{\nu_e}\, \underset{\downarrow}{\nu_\mu}$$



$$\frac{(\mu\text{-like})/(e\text{-like})\ \text{exp.}}{(\mu\text{-like})/(e\text{-like})\ \text{theor.}} \neq 1$$



Up/Down ≠ 1



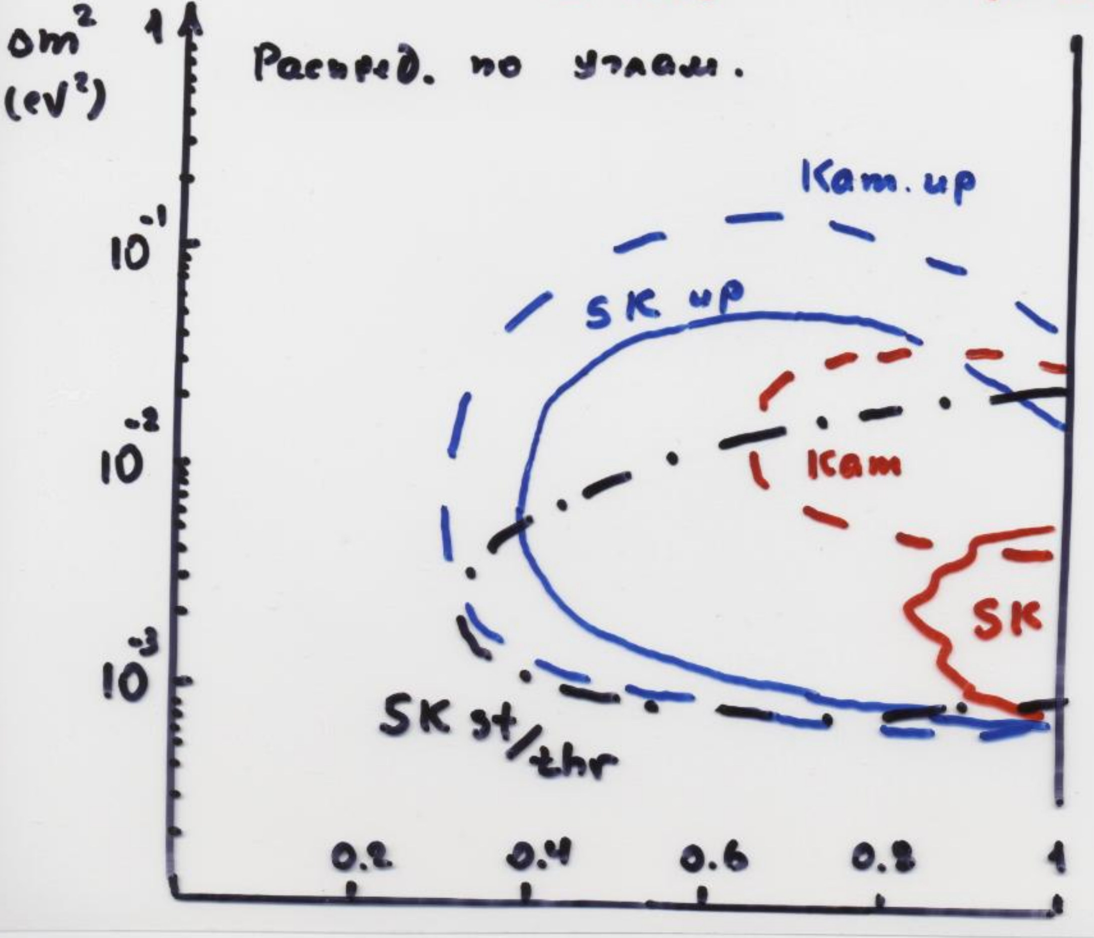
Kam	Kam	IMB	IMB	Frej.	Neusex	SoudanII
0.60	0.57	0.54	1.40	1.00	0.99	0.61
± 0.06	± 0.08	± 0.05	± 0.35	± 0.15	± 0.30	± 0.15
± 0.05	± 0.07	± 0.12	± 0.3	± 0.08	-	± 0.05
sub	mult	sub	mult			

Super - Kamiokande

(535 days)

		Data	Monte-Carlo Theory	$(^{\mu}/_{e})_{D} / (^{\mu}/_{e})_{Th.}$ st ↓ sys +th.
Sub GEV	1 Ring e-like	1231	1049	
	μ-like	1158	1574	0.63 ± 0.026 ± 0.05
	mul. Ring	911	981	
Multi GEV	1 Ring e-like	290	237	
	μ-like	230	298	0.65 ± 0.05 ± 0.08
	mul. Ring	533	560	

Up/Down $\quad 0.93 \pm 0.13$ e-like $\quad 0.54 \pm 0.06$ μ-like



$\sin^2 2\Theta > 0.8$

$\Delta m^2 \sim 10^{-3} \div \sim 10^{-2}\ eV^2$

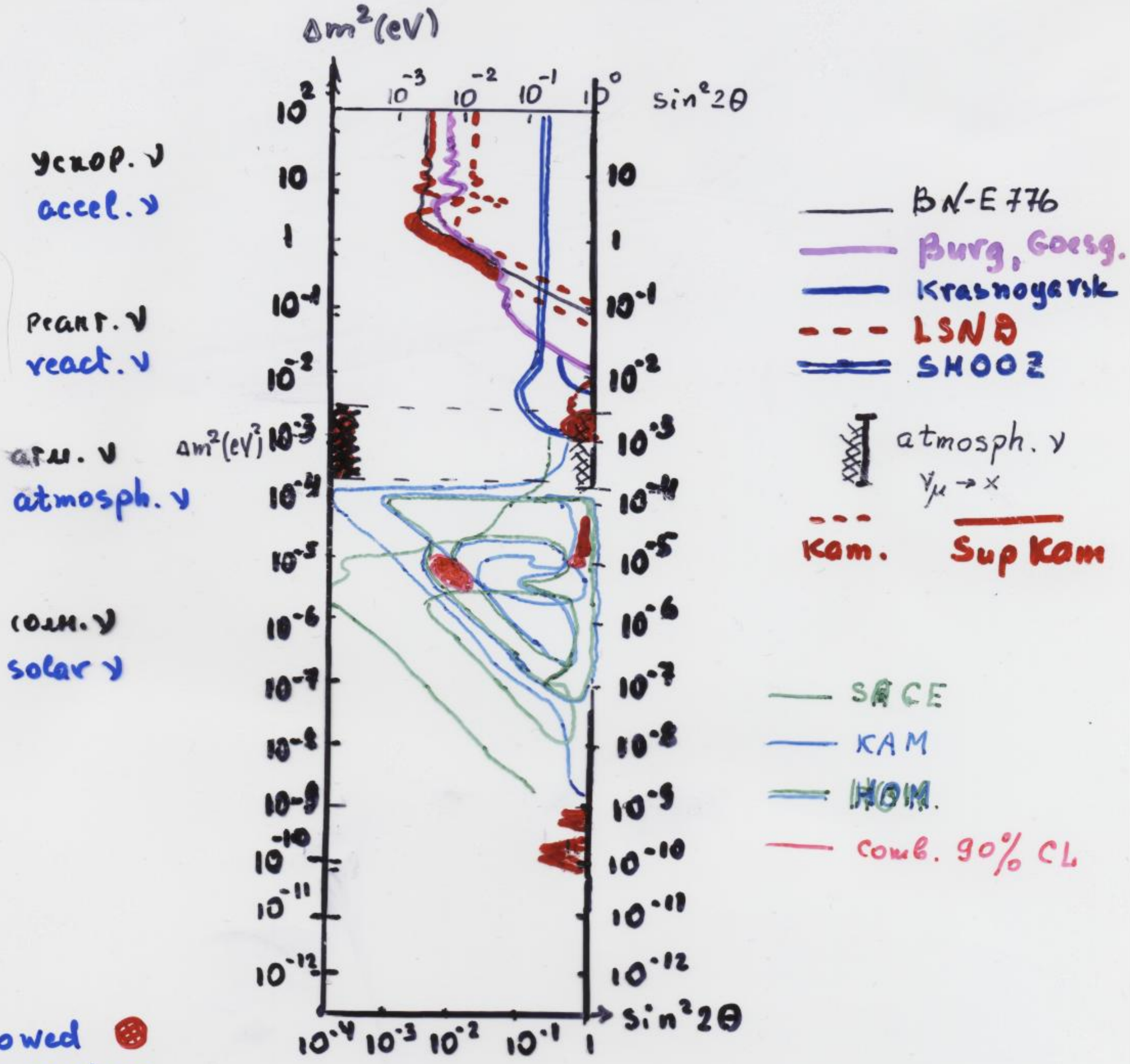
$\nu_\mu \rightarrow \nu_\tau$

or

$\nu_\mu \rightarrow \nu_{st.}$

Experimental results of Ga-Ge det. (sol. ν), ν-accel. experiments and reactor ν-experiments. Atmospheric ν-anomaly.

$$P_{\nu_1\to\nu_2}(r) = \frac{1}{2}\sin^2(2\theta)\,\sin^2\!\left(\frac{r}{E}\,|m_1^2-m_2^2|\right)$$



allowed ● osc. regions

Ожидаемые области ν-осцилл.

LSND 5 ÷ 0.5 $\underline{10^{-2}}$

SKamiок. $10^{-2} - 10^{-3}$ $\underline{>0.8}$

MSW - $5\cdot10^{-5}$ $\underline{0.85}$ $7\cdot10^{-6}$ $\underline{10^{-2}}$

Sun "Just so" $(0.9 \div 4)10^{-10}$ >0.5

– sin²2θ

New Projects (II gener.)

\+ SuperKamiokande: 50 000 T H_2O 11 000
(32 000 T)
aims: Solar ν, SN explosions

\+ KamLand: 1000 T liq. sc. 1300
aims: react. ν ~200 km, solar ν
atm. ν, SN expl., $\tilde{\nu}_e$ from Earth
2β-decay (Xe)

\+ SNO (Sudbury) 1000 T D_2O 9500
aims: νe, νD, solar ν,
atm. ν, SN expl., $n\bar{n}$

Borexino (Italy) 300 T liq. sc. 2000
Pilot 5 T " " 100
aims: Sol. ν ^7Be, atm. ν, $\tilde{\nu}_e$ from Earth
2β-dec. Gd, TB, Se

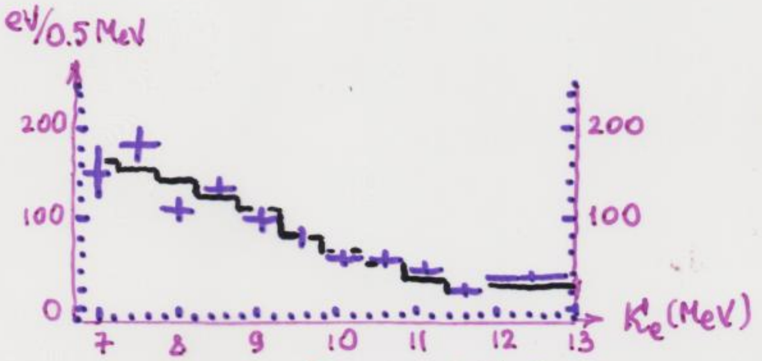
Long dist. ν experim.
Artif. ν sources ^{51}Cr, Pm
ν magn. moment

SNO (Canada), 2001

Первые результаты (First results of collab.)

$\nu_e + d \rightarrow p + p + e^- \text{ (c.c.)}$ $\nu_x + d \rightarrow p + n + \nu_x \text{ (n.c.)}$

$\nu_x + e^- \longrightarrow \nu_x + e^- \text{ (ES)}$



Спектр с K ≥ 6.75 МэВ

Ch. channel

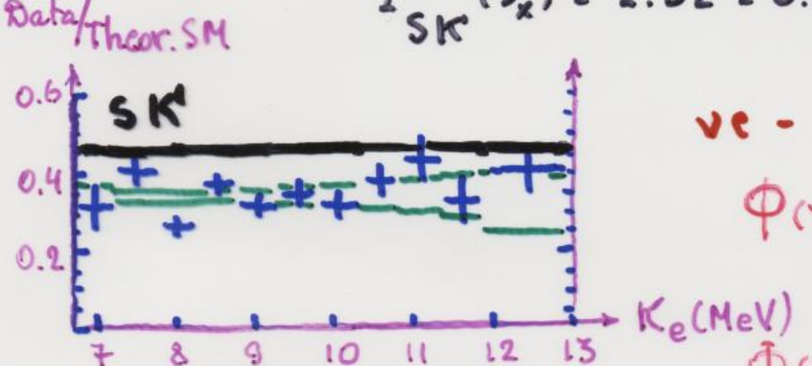
$$\Phi^{CC}_{(\nu_e)} = 1.75 \underset{\text{st.}}{\pm 0.07} \underset{\text{sys}}{{}^{+0.12}_{-0.11}} \underset{\text{th.}}{\pm 0.05}$$

$$\times 10^6 \text{ см}^{-2} \text{ сек}^{-1}$$

$$\Phi^{ES}_{(\nu_x)} = 2.39 \pm 0.34 {}^{+0.16}_{-0.14}$$

$$\times 10^6 \text{ см}^{-2} \text{ сек}^{-1}$$

$$\Phi^{ES}_{SK}(\nu_x) = 2.32 \pm 0.03 {}^{+0.08}_{-0.07} \times 10^6 \text{ см}^{-2} \text{ сек}^{-1}$$



Отношение набл. данных к солн. модели SK и SNO

νe - Neutr. channel

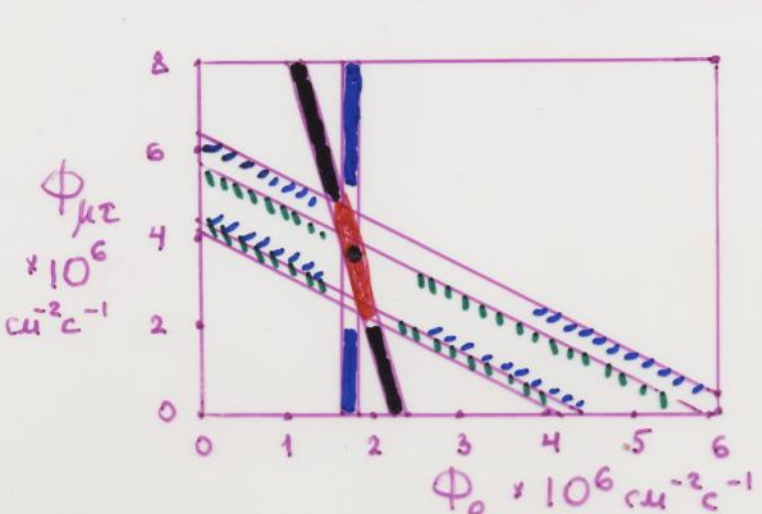
$$\Phi(\nu_{\mu\tau}) = 3.69 \pm 1.13 \cdot 10^6 \text{ см}^{-2} \text{ сек}^{-1}$$

$$\Phi(\nu_e) = 1.75 \pm 0.14 \cdot 10^6$$

$$\Phi(\nu_x) = 5.44 \pm 0.99 \cdot 10^6 \text{ см}^{-2} \text{ сек}^{-1}$$

согласуется с SM

coordinates with SM



▨ $\Phi^{CC}(\nu_e)$

▨ $\Phi^{ES}_{SK}(\nu_x)$

▨ SM (ν)

▨ $\Phi(\nu_x)$

▨ Разреш. район (1σ)

allowed region

νd - Neutral channel

Нейтр. канал: $\nu_x d$

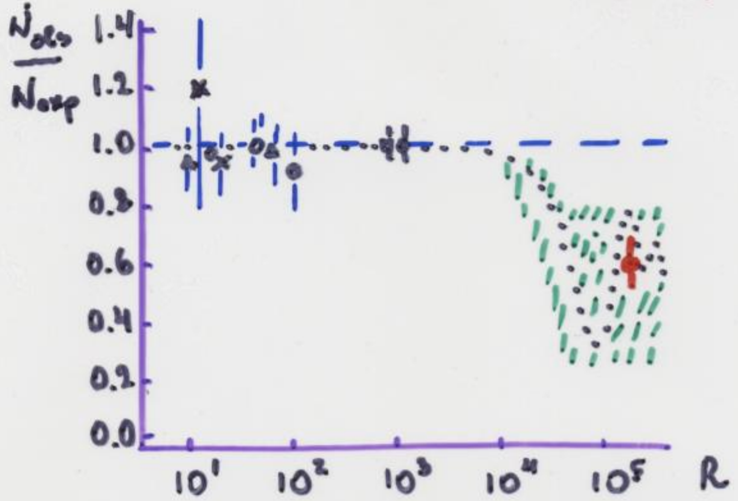
$$\Phi^{nc}(\nu_x) = 5.09 \pm 0.4 {}^{+0.46}_{-0.43} \times 10^6 \text{ см}^{-2} \text{ сек}^{-1}$$

$$4.90 \pm 0.24 \pm 0.29 \times 10^6 \text{ см}^{2} \text{ сек}^{-1}$$

KamLAND Data (2003)

$\bar{\nu}_e + p \to n + e^+$

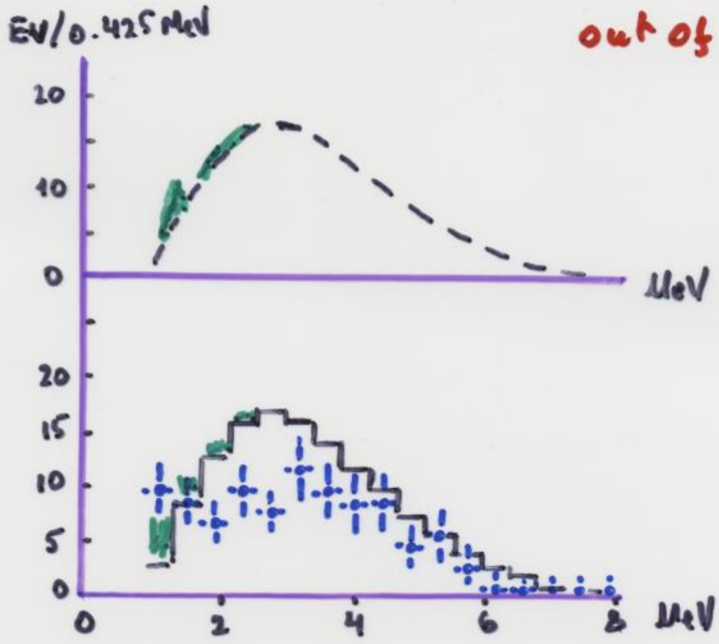
162 t



ILL, Savannah River, Bugey, Rovno
Goesgen, Krasnoyarsk, Paolo Verde,
Chooz, KamLAND

$$\frac{N_{obs} - N_{BG}}{N_{expect.}} = 0.611 \underset{stat}{\pm 0.085} \underset{syst}{\pm 0.041}$$

out of SM (99.95%)



$\sin^2 2\theta = 1.0 \qquad \Delta m^2 = 6.9 \cdot 10^{-5}\,eV^2$ (R)

$\sin^2 2\theta = 0.91 \qquad \Delta m^2 = 6.9 \cdot 10^{-5}\,eV^2$ (spectrum)

Summary of Neutrino-2004

Oscillation parameters:

$\Delta m^2_{atm.} = 2.5\cdot10^{-3}\,eV^2\ (\pm0.5)$ SK + K2K

$\Delta m^2_{sol} = 8\cdot10^{-5}\,eV^2\left({+0.6 \atop -0.5}\right)$ Kam.I + SNO(salt)

$(\Delta m^2_{LSND} \sim 1\,eV^2\ ?)$

θ_{23} (atm) large $\sin^2 2\theta_{23} = 1.00$ K2K

θ_{12} (sol) large $tg^2\theta_{12} = 0.40^{+0.09}_{-0.07}$ KamI + SNO(salt

θ_{13} (CHOOZ) small $\sin^2\theta_{13} < 0.061$

$0.8\cdot10^{-3} \leq m_\nu \leq 0.5$ (eV)

Direct mass measurements

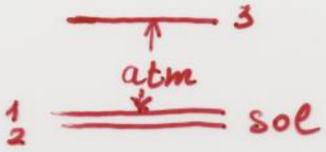
$m_{\nu e} < 2.2\,eV$

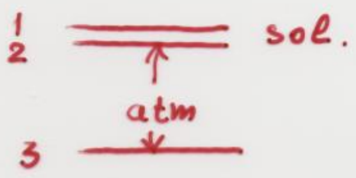
$m_{\nu\mu} < 170\,keV$

$m_{\nu\tau} < 18.2\,MeV$

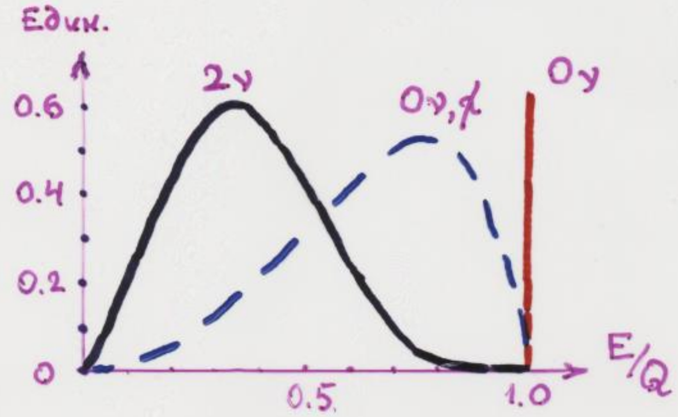
Cosmology $m_\nu < 0.23 \div 0.7\,eV$

$$U = \begin{pmatrix} 0.84 & 0.54 & 0.1 \\ -0.44 & 0.56 & 0.71 \\ 0.32 & -0.63 & 0.71 \end{pmatrix}$$





2β - 2ν - распад. - decay



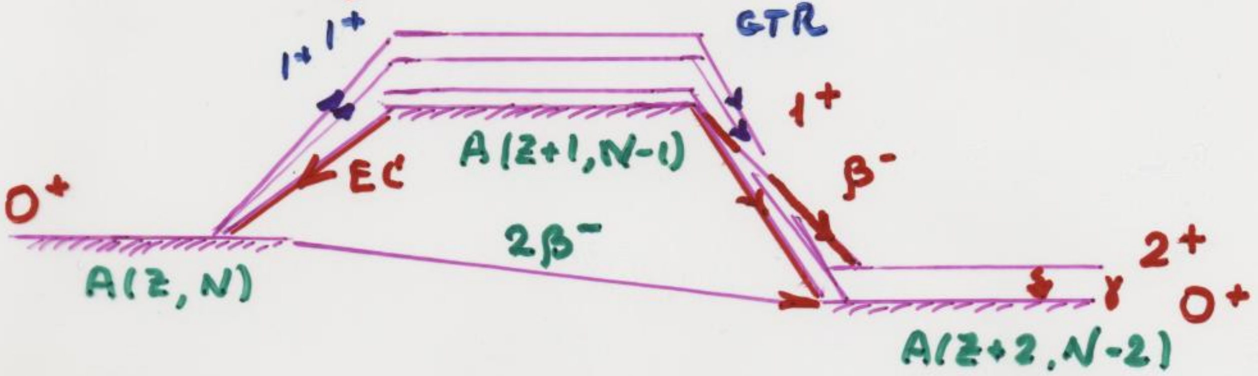
$A(Z,N) \to A(Z+2,N-2)+$

$+\,2e^- + 2\nu$ (2ν)

$+\,2e^- + \chi_M$ (0ν,χ)

$+\,2e^-$ (0ν)

$$(T_{1/2}^{2\nu})^{-1} = F^{2\nu}|M^{2\nu}|^2$$



$$T_{1/2}^{2\nu} = \frac{G_\beta^4 g_A^4 m_e^9}{96\ln 2}|M^I M^F|^2 \int d\varepsilon_1 d\varepsilon_2 d\omega\, F_1 F_2\, p_1\varepsilon_1 p_2\varepsilon_2\, \omega_1^2\omega_2^2\, D(K,L)$$

$$D(K,L) = \begin{cases} K^2+L^2+KL & (00) \\ (K-L)^2 & (02) \end{cases}$$

$$K = [\mu_1 + (\varepsilon_1+\omega_1-\varepsilon_2-\omega_2)/2]^{-1} + [\mu_1 - (\varepsilon_1+\omega_1-\varepsilon_2-\omega_2)/2]^{-1},$$

$$L\,(\omega_1 \leftrightarrow \omega_2).$$

$$\mu_1 = E - \frac{M_i+M_f}{2}$$

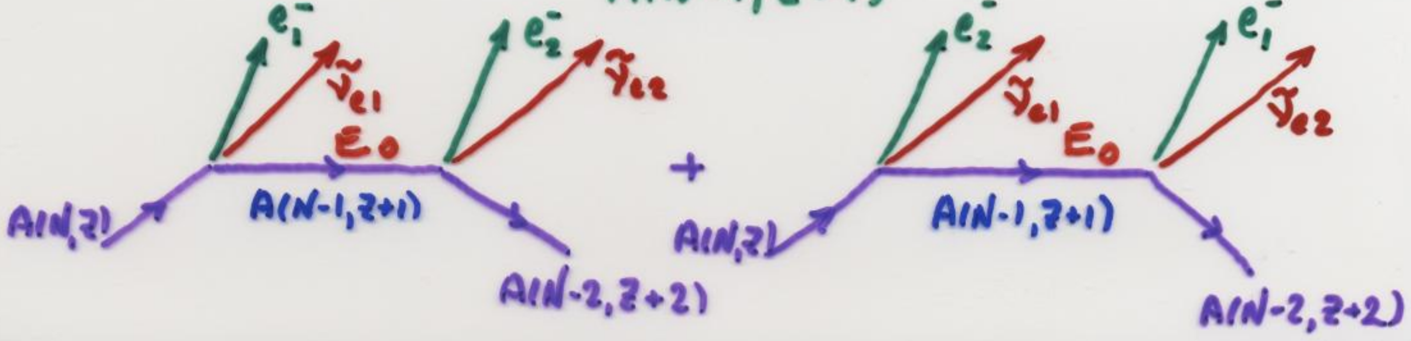
SSD - approxitamion!

Приближение: 1^+ сост. $A(N-1,Z+1)$ - основное!

$$T_{1/2}^{2\nu} \approx 3\cdot10^{14}\,\text{yr}\,(ft)_{EC}\,(ft)_{\beta^-} / H(Q_{\beta\beta}, J_f)$$

для 1^+ осн. состояния (1^+ground state)

$A(N-1,Z+1)$



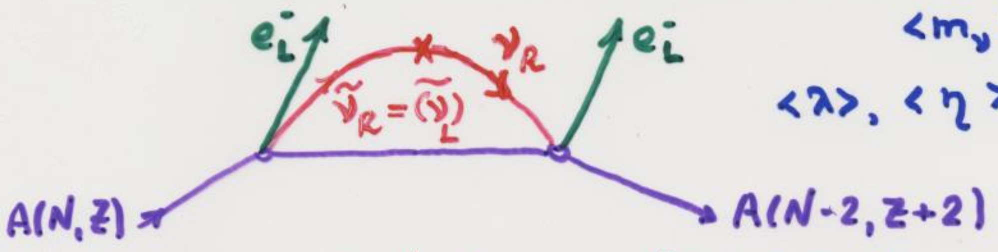
2β - 0ν - распад - decay

$$(T_{1/2}^{0\nu})^{-1} = \langle m_\nu\rangle^2 / m_e^2 \; F^{0\nu} |M^{0\nu}|^2$$

$$\lim T_{1/2}^{0\nu} \approx (4.18\cdot 10^{24}\,\text{кг}^{-1}) \frac{a}{f}\sqrt{\frac{M\varepsilon t}{\beta \Delta E}}$$

a - обогащение , M - масса·год

β - фон , ΔE - разрешение , ε - эффект.



$\langle m_\nu\rangle$ - майор. масса

$\langle\lambda\rangle$, $\langle\eta\rangle$ - R - токи

$$A(N,Z) \longrightarrow A(N-2,Z+2) + 2e^-$$

$$(T_{1/2}^{0\nu})^{-1} \sim C_{mm}\langle m_\nu\rangle^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{m\eta}\langle m_\nu\rangle\langle\eta\rangle + C_{m\lambda}\langle m_\nu\rangle\langle\lambda\rangle + C_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle$$

A(N,Z)	$T_{1/2}^{0\nu}$ лет	$\langle m_\nu\rangle$, эВ
^{48}Ca	$> 1.5\cdot 10^{21}$	< 0
^{76}Ge	$> 1.6\cdot 10^{25}$	$< 0.4 \div 1.07$
^{82}Se	$> 2.7\cdot 10^{22}$	$< 4.7 \div 9.4$
^{96}Zr	$> 1\cdot 10^{21}$	< 23
^{100}Mo	$> 5.2\cdot 10^{22}$	$< 2.2 \div 4.9$
^{116}Cd	$> 3.2\cdot 10^{22}$	< 4.1
^{128}Te	$> 7.7\cdot 10^{24}$	< 1.2
^{130}Te	$> 5.6\cdot 10^{22}$	< 2.9
^{136}Xe	$> 4.4\cdot 10^{23}$	$< 1.8 \div 5.2$
^{150}Nd	$> 1.2\cdot 10^{21}$	$< 5.3 \div 20$

^{76}Ge, данные коллаб.

$> 1.9\cdot 10^{25}$ л. < 0.2 эВ

Klapdor, 2002

$0.2 \lesssim \langle m_\nu\rangle \lesssim 0.5$

$\langle\lambda\rangle < 10^{-9}$ eV

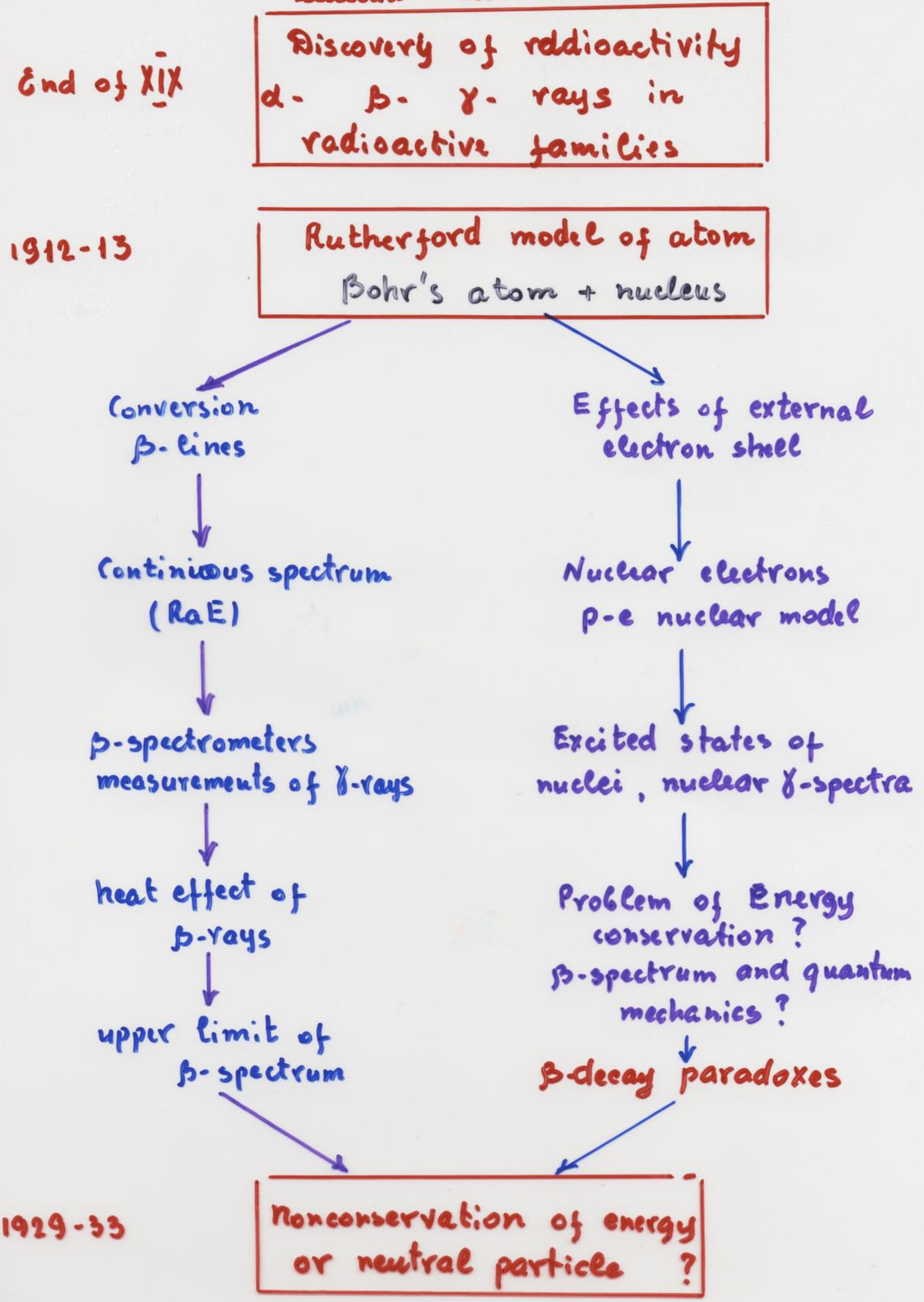
$\langle\eta\rangle < 10^{-7}$ eV

$$A(N,Z) + e^- \longrightarrow A(N+1, Z-1) + e^+$$

$$A(N,Z) \longrightarrow A(N+2, Z-2) + 2e^+$$ Нет данных.

$$A(N,Z) + 2e^- \longrightarrow A(N+2, Z-2) + \gamma$$ no date !

Resume of the report.



End of XIX

Discovery of radioactivity
α- β- γ- rays in
radioactive families

1912-13

Rutherford model of atom
Bohr's atom + nucleus

Conversion
β- lines

Continious spectrum
(RaE)

β-spectrometers
measurements of γ-rays

heat effect of
β-rays

upper limit of
β- spectrum

Effects of external
electron shell

Nuclear electrons
p-e nuclear model

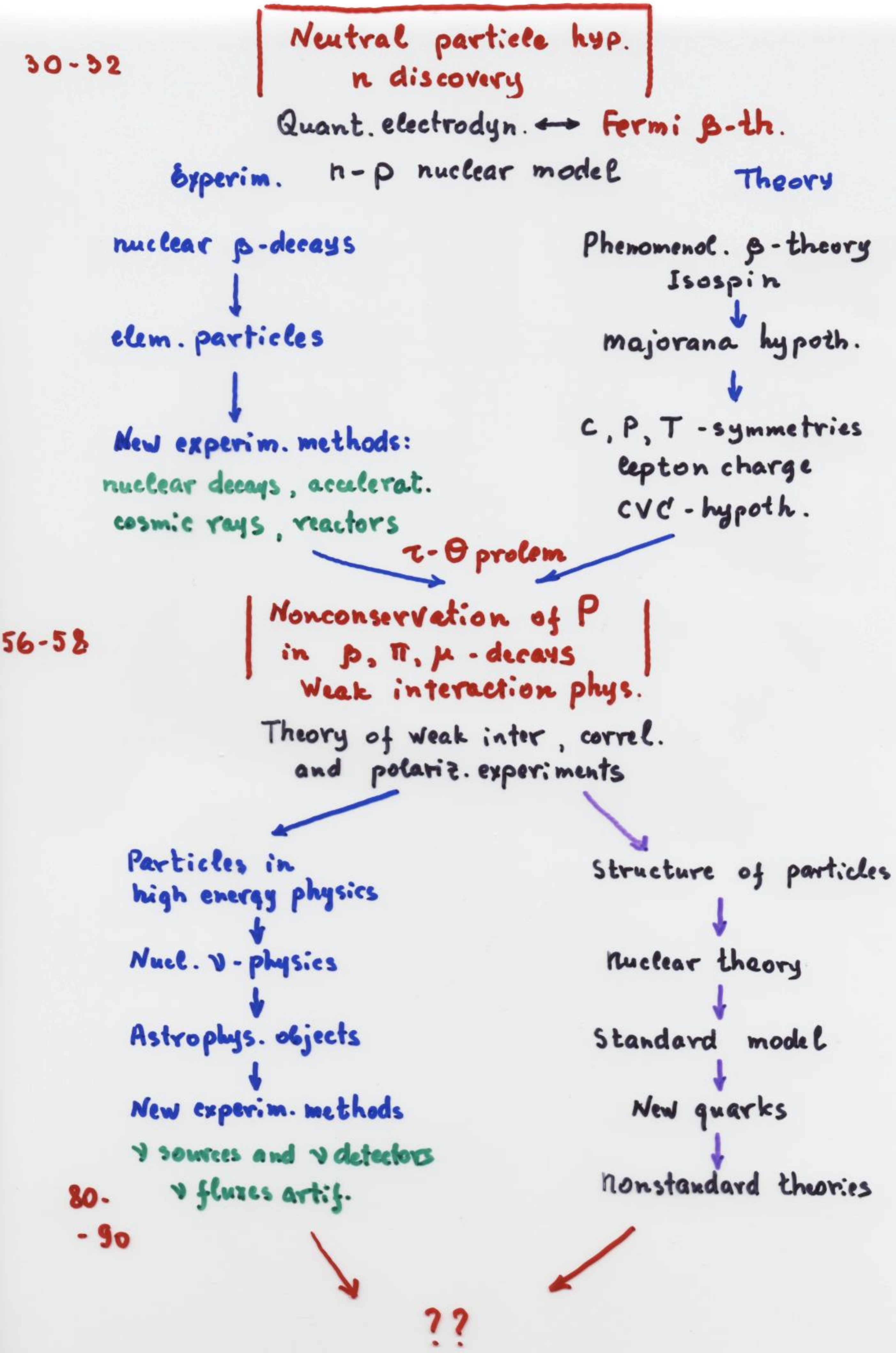
Excited states of
nuclei, nuclear γ-spectra

Problem of Energy
conservation ?
β-spectrum and quantum
mechanics ?

β-decay paradoxes

1929-33

Nonconservation of energy
or neutral particle ?



30-32

Neutral particle hyp.
n discovery

Quant. electrodyn. ↔ Fermi β-th.

Experim. n-p nuclear model Theory

nuclear β-decays
↓
elem. particles
↓
New experim. methods:
nuclear decays, accelerat.
cosmic rays, reactors

Phenomenol. β-theory
Isospin
↓
Majorana hypoth.
↓
C, P, T -symmetries
lepton charge
CVC - hypoth.

τ-Θ prolem

56-58

Nonconservation of P
in β, π, μ - decays
Weak interaction phys.

Theory of weak inter, correl.
and polariz. experiments

Particles in
high energy physics
↓
Nucl. ν - physics
↓
Astrophys. objects
↓
New experim. methods
ν sources and ν detectors
ν fluxes artif.

80-
-90

Structure of particles
↓
Nuclear theory
↓
Standard model
↓
New quarks
↓
Nonstandard theories

??

Beyond Standard Model Phenomena

Solar ν-experim.
ν_e-deficite

↓

Atmospherecal ν
ν_μ-deficit

↓

SNO - experiments
$\nu_e \to \nu_x$

↓

Reactor ν-experim.
KamLand, $m_\nu > 10^{-2}$ eV !

↓

2β-0ν-decay, m_ν - ??

↓

Anomal. magnetic
ν-moment $\mu_\nu < 10^{-10} \mu_e$

μ_ν ?

↓

Direct measurements
$m_{\nu e}$ Anomalies !

↓

$\pi \to e\nu\gamma$-anomaly ??

↓

⋮

Models of ν-oscil.
in vacuum and
substance MSW

↓

majorana neutrino
$\nu = \nu^c$

↓

magnetic properties
of ν

VVO, LMA

↓

Nuclear models
of 2β-2ν, 2β-0ν

↓

Mayorana ν theory ?

↓

Connection with
Standard Model ?

↓

⋮

Acknowledgments :

The author is very grateful to Organizing committee of the International School for their support, permanent interest to history of neutrino physics and the possibility for the author to make this report at special session in a free stile.

This work was supported by the grant N 14 of RRC "Kurchatov Institute" of 2003-04 years and by the RFBR grant N 03-02-17266 of 2003-04 years on fundamental research.