(229)

pt. 1-2

Cours/Lecture Series

1989-1990 ACADEMIC TRAINING PROGRAMME

SPEAKER	: B. DEGRANGE / Ecole Polytechnique, Palaiseau
TITLE	: Non accelerator physics , pt. 1
DATES	: 19, 20, 21, 22 & 23 February
TIME	: 11.00 to 12.00 hrs
PLACE	: Auditorium

COURS 1 and 2

ABSTRACT

In recent years, an important development of non-accelerator experiments in Particle Physics can be noted. New underground facilities for operating large detectors are available and new projects of large surface arrays for cosmic-ray physics are proposed or being built. This growing interest was motivated by Grand Unified Theories predicting baryon and lepton number violations, but also by some astrophysical problems strongly connected to Particle Physics, e.g. the Solar Neutrino puzzle or the nature of 'dark matter', and by the detection of high energy gamma-rays or neutrinos of cosmic origin.

The above topics cover very different ranges in energy and various detection techniques and such a review cannot be completely exhaustive. Emphasis will be put on the following fields : search for nucleon decay; search for neutrinoless double beta decay; astrophysical problems at low energy (solar neutrinos and dark matter); cosmic-ray physics (search for high energy neutrinos; cosmic-ray chemical composition in the PeV range).

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Cours 1

NON ACCELERATOR
PARTICLE PHYSICS

B. DEGRANGE
FEBRUARY 1990.

NON ACCELERATOR STUDIES

STABILITY OF MATTER

- NUCLEON DECAY
- DOUBLE BETA DECAY

NEUTRINOS

- REACTOR $\bar{\nu}_e$'s
- ATMOSPHERIC ν's
- ν's FROM STELLAR COLLAPSE
- SOLAR NEUTRINOS

COSMIC RAYS

- EXTENSIVE AIR SHOWERS
- VERY HIGH ENERGY γ-RAY & NEUTRINO ASTRONOMIES

NEW PARTICLES
(COSMOLOGICAL ORIGIN)

- WEAKLY INTERACTING (ASSIVE PARTICLES
- MONOPOLES

MOTIVATIONS FROM PARTICLE PHYSICS

BARYON NUMBER violation

LEPTON NUMBER violation

NEUTRINO properties

- ν FLAVOUR MIXING
- ν OSCILLATIONS OR DECAYS
- ν MASSES
- WHY $m_\nu << m_{\ell^\pm}$?
- MAJORANA ν: $\Delta L = 2$

PREDICTED PARTICLES

- SUSY
- AXION
- MAJORON
- MONOPOLE

BEYOND PRESENT ACCELERATORS

COSMIC RAY PHENOMENA

MOTIVATIONS FROM ASTROPHYSICS

COSMOLOGY

- needs baryon number violation (Baryon-Antibaryon asymmetry)
- needs DARK MATTER (LIKELY TO BE NON-BARYONIC)

SUPER NOVA THEORY

STANDARD SOLAR MODEL

contradicted by ^{37}Cl Experiment and Kamiokande II exp^t

ORIGIN OF COSMIC RAYS

Acceleration mechanisms

Localize γ-ray sources

Localize ν - sources

Find chemical compos^n of very high energy C.R.

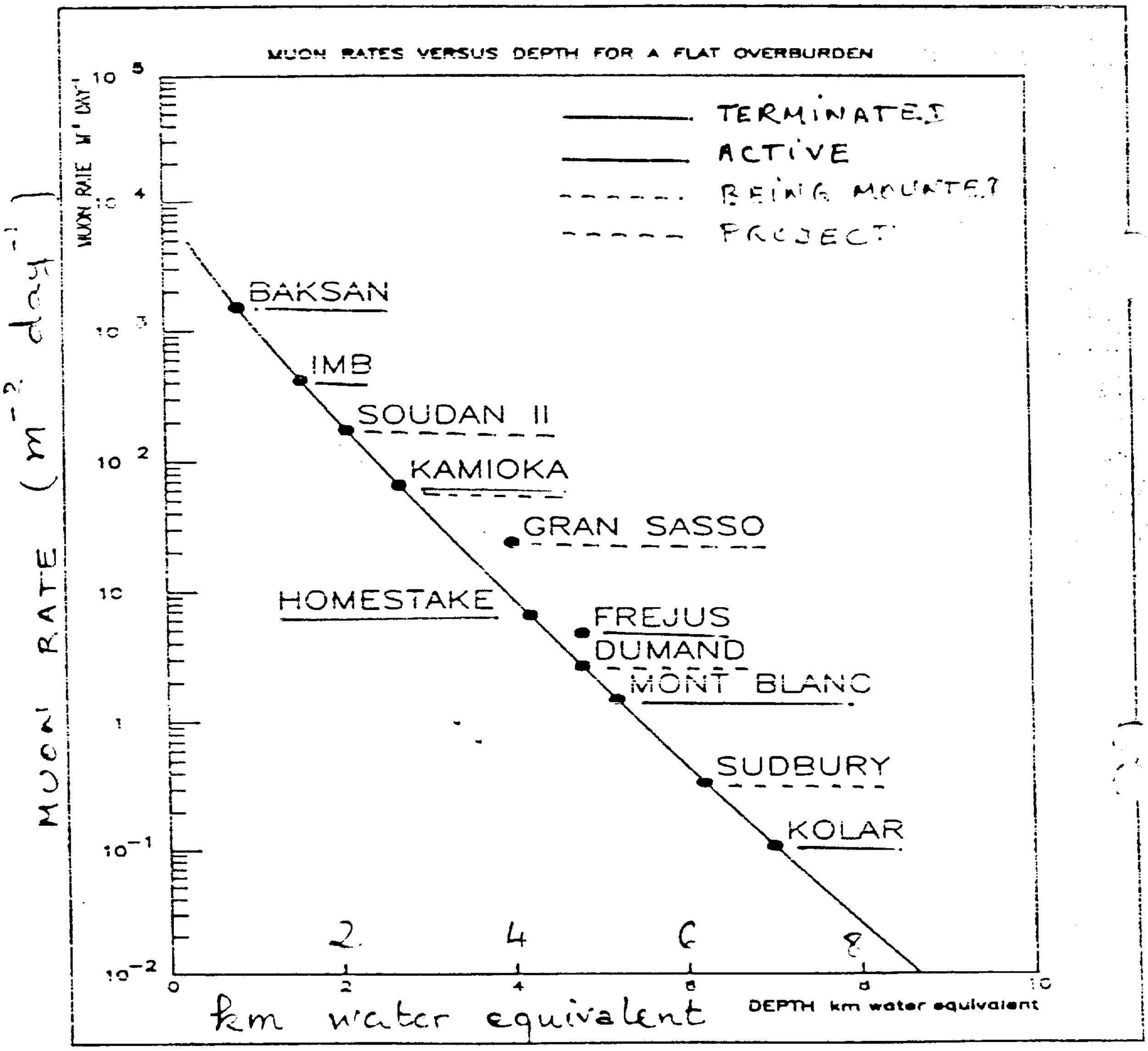
NON ACCELERATOR PARTICLE PHYSICS.

EXPERIMENTAL SITES

- REACTORS (n source / $\bar{\nu}_e$ source)
- UNDERGROUND EXPERIMENTS
- GROUND-BASED COSMIC RAY EXPTS (often mountain altitude)

WHY UNDERGROUND EXPERIMENTS :

10 years ago : Mainly small experiments ; few underground labs.



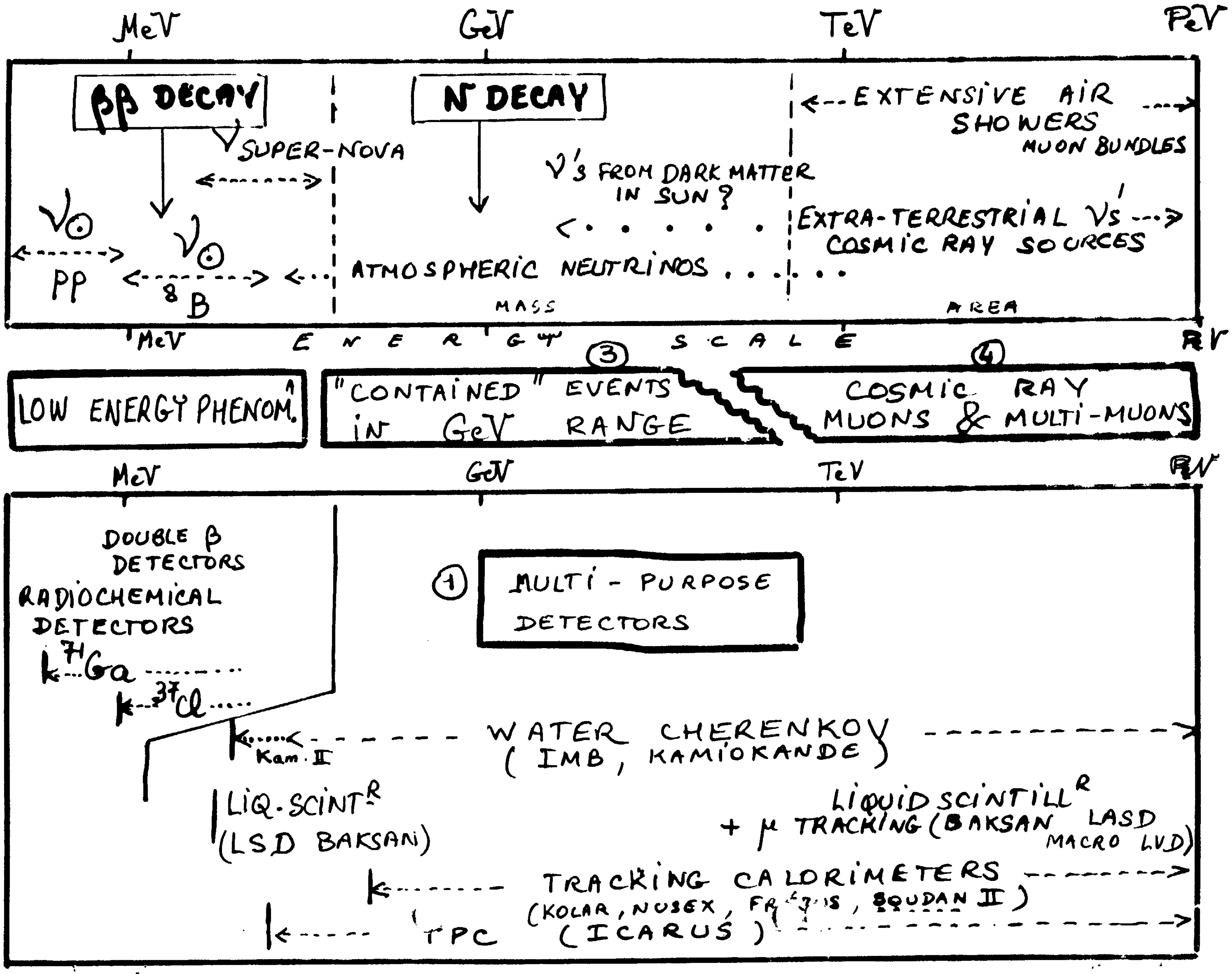
Now : LARGE UNDERGROUND EXP^L HALLS

DETECTORS WITH MASSES $\gtrsim$ 1000 tonn

AREAS $\gtrsim$ 100 m^2

NEXT FUTURE : INCREASE MASS (SUPERKAMIOKA 32 000 tonne)

AREA (MACRO 1000 m^2)


MeV
GeV
TeV
PeV
ββ DECAY
N DECAY
ν SUPER-NOVA
EXTENSIVE AIR SHOWERS
MUON BUNDLES
ν's FROM DARK MATTER IN SUN ?
ν⊙ PP
ν⊙ 8B
ATMOSPHERIC NEUTRINOS
EXTRA-TERRESTRIAL ν's
COSMIC RAY SOURCES
MASS
AREA
ENERGY SCALE
② LOW ENERGY PHENOM.
③ "CONTAINED" EVENTS IN GeV RANGE
④ COSMIC RAY MUONS & MULTI-MUONS
DOUBLE β DETECTORS
RADIOCHEMICAL DETECTORS
71Ga
37Cl
① MULTI - PURPOSE DETECTORS
Kam. II
WATER CHERENKOV (IMB, KAMIOKANDE)
LIQ. SCINTR (LSD BAKSAN)
LIQUID SCINTILLR + μ TRACKING (BAKSAN LASD MACRO LVD)
TRACKING CALORIMETERS
(KOLAR, NUSEX, FR, SOUDAN II)
TPC (ICARUS)

NON ACCELERATOR PARTICLE PHYSICS

I. SEARCH FOR BARYON NUMBER VIOLATION

1 • Nucleon decay
• Neutron - Antineutron oscillations ($\Delta B = 2$)

II SEARCH FOR DOUBLE BETA DECAY ($\Delta L = 2$)

2 • Dirac vs. Majorana ν-mass terms.
• Double beta decay & ν masses.
• Experiments on double beta decay.

III. NEUTRINO PHYSICS

• Neutrino oscillations (vacuum + matter)
3 • Reactor experiments
• Atmospheric neutrinos
• Neutrinos from stellar collapse

• Solar neutrinos.

4
IV PARTICLES FROM COSMOLOGICAL ORIGIN

• Dark matter

V COSMIC-RAY PHYSICS

5 • Very (Ultra) High Energy γ-ray and neutrino astronomy.
• Cosmic-ray composition above 1 TeV

PART 1 : SEARCH FOR BARYON-NUMBER-VIOLATING PROCESSES

- PREDICTIONS OF GRAND UNIFIED THEORIES
  - $\Delta B = 1$
  - $\Delta B = 2$
- NUCLEON DECAY EXPERIMENTS
  - General features
  - Detectors
  - Channel per channel analysis
  - Results
- NEUTRON - ANTINEUTRON OSCILLATIONS
  - General features
  - Experiments & results
- CONCLUSION

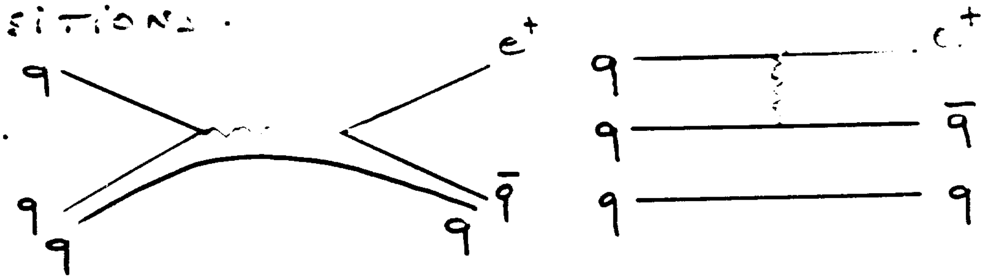
1. GENERAL PREDICTIONS OF GRAND UNIFIED THEORIES

- "GRAND UNIFICATION" SYMMETRY VALID AT ~ 10^{14} GeV (e.g. SU(5), SO(10), ...)

  - QUARKS AND LEPTONS BELONG TO SAME MULTIPLETS.

  - SUPERMASSIVE BOSONS INDUCE QUARK-LEPTON TRANSITIONS.

e.g.



- THE ORIGINAL SYMMETRY IS SPONTANEOUSLY BROKEN (MAYBE IN SEVERAL STEPS), SO THAT ONE EVENTUALLY REMAINS WITH:

  $SU(3)_c \times SU(2)_L \times U_1$ (STAND.D MODEL)

  → THERE MAY BE SEVERAL INTERMEDIATE MASS SCALES BETWEEN 10^{14} GeV AND 10^2 GeV.

  (e.g. W_R, Z' in L-R THEORIES, SUPERSYMMETRIC PARTICLES ...)

BARYON NUMBER VIOLATION

$\Delta B = \Delta L = -1$ FAVOURED

$$\mathcal{L}_{eff.} = G_{eff.}\, qqq\, \ell$$

FROM DIMENSIONAL ARGUMENTS : $G_{eff.} \propto \frac{1}{M^2}$ (LOWEST POWER IN M)

M : HEAVY BOSON MASS

NUCLEON DECAY : [illegible]

e.g.
- $p \to e^+ \pi^0$ $\quad p \to \mu^+ K^0$ ...
- $p \to \bar{\nu}_\mu \pi^+$ ...
- $p \to \bar{\nu}\, K^+$ (FAVOURED BY SUPERSYMMETRY)

$\Delta B = -\Delta L = -1$?

$$\mathcal{L}_{eff.} = G_{eff.}\, qqq\, \bar{\ell}\, \underbrace{B}_{\text{BOSON FIELD}}$$

(MUST SATISFY
- LORENTZ
- $SU(3)_c \times SU(2)_L \times U(1)$)

FROM DIMENSIONAL ARGUMENTS : $G_{eff.} \propto \frac{1}{M^3}$

- SIGNIFICANT ONLY IF $M_I \ll M$ (GRAND UNIF^N)
- (INTERMEDIATE MASS SCALE)

NUCLEON DECAY : e.g. $p \to e^- \pi^+$ ...

$\Delta B = 2$; $\Delta L = 0$?

$$\mathcal{L}_{eff.} = G_{eff.}\, qqq\, qqq \qquad G_{eff} \propto \frac{1}{M^5}$$

SIGNIFICANT ONLY IF $M_I \ll M$ (GRAND UNIF^N)

NEUTRON - ANTINEUTRON OSCILLATIONS.

2. NUCLEON · DECAY EXPERIMENTS

2.1 GENERAL FEATURES

τ (p OR BOUND n LIFETIME) WAS INITIALLY PREDICTED (e.g. SU(5)) AT THE LEVEL OF 10^{31} years

• DETECTORS WITH MASSES $\gtrsim$ 1000 tonnes

EXPECTED NUMBER OF EVENTS IN A DECAY MODE WITH BRANCHING RATIO B :

$$N = \underbrace{f}_{\text{fraction of the relevant nucleon}} \times \underbrace{6.10^{23} \times 10^{9}}_{\text{number of nucleons per 1000 tonnes}} \times \boxed{M \times T} \times \underbrace{\varepsilon}_{\text{overall efficiency}} \times \boxed{\frac{B}{\tau}}$$

FRACTION OF THE RELEVANT NUCLEON: $\frac{p}{p+n}$ OR $\frac{n}{p+n}$

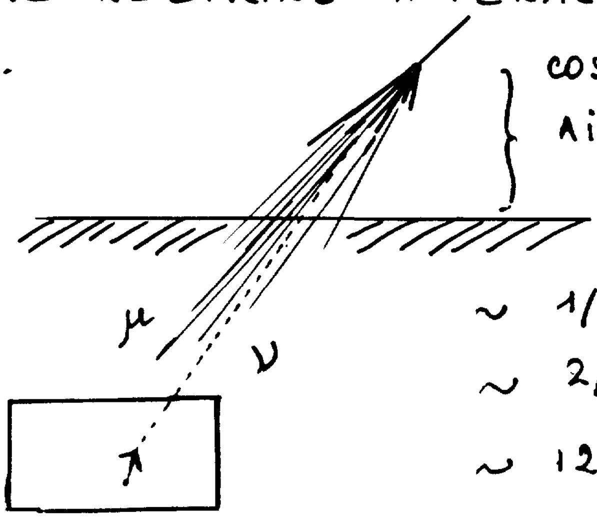
NUMBER OF NUCLEONS PER 1000 TONNES

OVERALL EFFICIENCY

$M \times T$: FIDUCIAL MASS in kilotonnes × EXPOSURE TIME — "LUMINOSITY" (kt × years)

• DETECTORS MUST ALLOW A GOOD BACKGROUND REJECTION.

MAIN BACKGROUND IN DEEP UNDERGROUND EXP^{TS}: ATMOSPHERIC NEUTRINO INTERACTIONS IN THE DETECTOR.



COSMIC-RAY AIR SHOWER

~ 1/3 $\nu_e \bar{\nu}_e$

~ 2/3 $\nu_\mu \bar{\nu}_\mu$

~ 120 ν-INT^{NS}/(kt · year)

NUCLEON DECAY EXPERIMENTS
GENERAL FEATURES.

DISCRIMINATION AGAINST $\nu(\bar{\nu})$ BACKGROUND

$\sim$ 120 $\nu(\bar{\nu})$ INTERACTIONS / (kilotonne x year)

BUT MOST OF THOSE EVENTS CANNOT BE CONFUSED WITH NUCLEON DECAYS AND ARE REMOVED BY SELECTION CRITERIA :

- EVENT MUST BE FULLY CONTAINED.
- TOPOLOGICAL REQUIREMENTS.
  (depending on decay-mode of interest
- KINEMATICAL CONSTRAINTS
  (E ≈ M. for modes with a charged lepton
  $\Delta E/E$, ANGULAR RESOLUTION

FOR LARGE EXISTING DETECTORS

(IMB , KAMIOKANDE , FRÉJUS , SOUDAN.

AND FOR MOST OF THE MODES ,
THE REMAINING BACKGROUND RATE

$$R_B \lesssim \text{several events} / (\text{kilotonne} \times \text{year})$$

depending on the decay mode.

* IN SOME FAVOURABLE CASES , IT IS MUCH LOWER AND THUS NEGLIGIBLE. ($e^+\pi^0$; $e^+\gamma$)

NUCLEON DECAY EXPERIMENTS

GENERAL FEATURES

OWER BOUND ON τ / B FOR
A NUCLEON DECAY MODE.

2 LIMITING CASES :

- BACKGROUND is NEGLIGIBLE.

  0 Events observed

$$\underset{\text{(90\% C.L.) years}}{\tau / B} > \underbrace{f}_{\frac{p}{n+p} \text{ or } \frac{n}{n+p}} \frac{6 \cdot 10^{32}}{2.3} \underbrace{\boxed{M_F \cdot T}}_{\text{LUMINOSITY (kilotonne} \times \text{years)}} \underbrace{\boxed{\varepsilon}}_{\text{OVERALL DETECT}^{N} \text{ EFFICIENCY}}$$

- BACKGROUND WITH GAUSSIAN ERRORS.

  Number of observed candidates is compatible with background expectation.

  | R_B = BACKGROUND RATE / (kilotonne · year) |

$$\underset{\text{(90\% C.L.)}}{\tau / B} > f \frac{6 \cdot 10^{32}}{1.65} \sqrt{\frac{M_F T}{R_B}} \quad \varepsilon$$

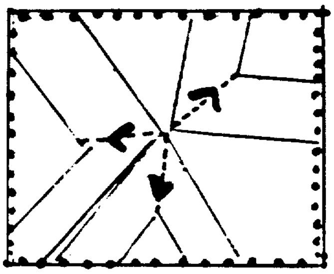
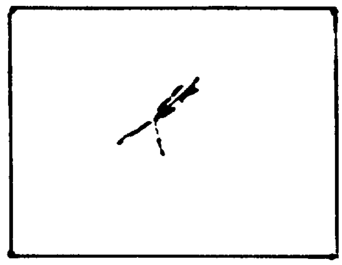
GENERAL CASE : USE POISSON STATISTICS

BUT THE KEY PARAMETERS OF THE CALCULATION ARE :

$$\left\{ \begin{array}{l} M_F . T \\ \varepsilon \\ R_B \end{array} \right.$$

2.2 DETECTORS

TWO EXPERIMENTAL TECHNIQUES

WATER CHERENKOV	TRACKING CALORIMETERS
 CHERENKOV RINGS + TIME INFORM^N	 VERTEX + TRACKS
+ LARGE MASSES (e.g. IMB 8000 tonnes → 3300 fiduc! !!) + SENSE OF TRACK DIRECT^N + FREE PROTONS	+ HIGH SPATIAL RESOL^N (Multi-track / multi-vertex) + BETTER π^0/μ DETECT^N AT E ~ 100-200 MeV + SOUDAN II : dE/dx

SENSITIVITY FOR PRESENTLY PUBLISHED DATA (ALL EXPERIMENTS) ~ 11000 tonnes x years.

NUCLEON DECAY DETECTORS

WATER CHERENKOV

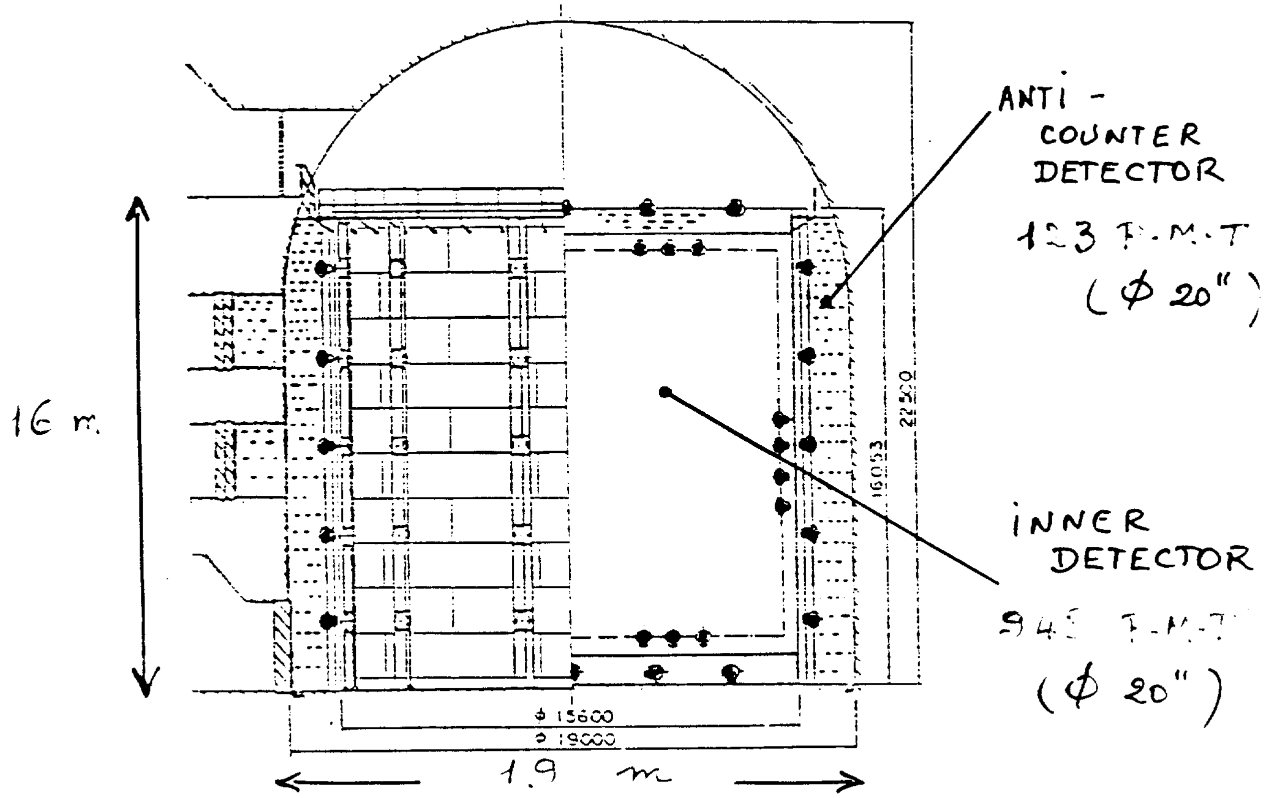
DETECTOR	TOTAL MASS (tonnes)	FIDUCIAL MASS (tonnes)	% OF LIGHT COLLECTED	SPATIAL RESOLUTION (cm)
I.M.B. I / III	8000	3300	2% / 8%	~ 100
KAMIOKA I / II	3000	880 / 780 + ACTIVE SHIELD	20%	~ 20

TRACKING CALORIMETERS (Fe / Iron plates sandwich)

DETECTOR	TOTAL MASS (tonnes)	FIDUCIAL MASS (tonnes)	DETECTION TECHNIQUE	SAMPLING DIST^{CE} IN Fe cm	$\frac{dE}{dx}$	SPATIAL RESOLUTION (cm)
KOLAR GOLD FIELDS I / II	140 / 260	60 / 160	PROPORT. TUBES	1.2 / 0.6	YES	10
NUSEX	150	113	STREAMER TUBES	1	–	1
FRÉJUS	912	550	FLASH CHAMBERS + Geigers	0.3	–	0.5
SOUDAN II	~500 (→ 1000?)	?	DRIFT TUBES	0.3	YES	0.5

KAMIOKANDE II CHERENKOV DETECTOR

(KAMIOKA MINE, JAPAN
2700 m.w.e.)



TOTAL MASS : 3000 tonnes of water

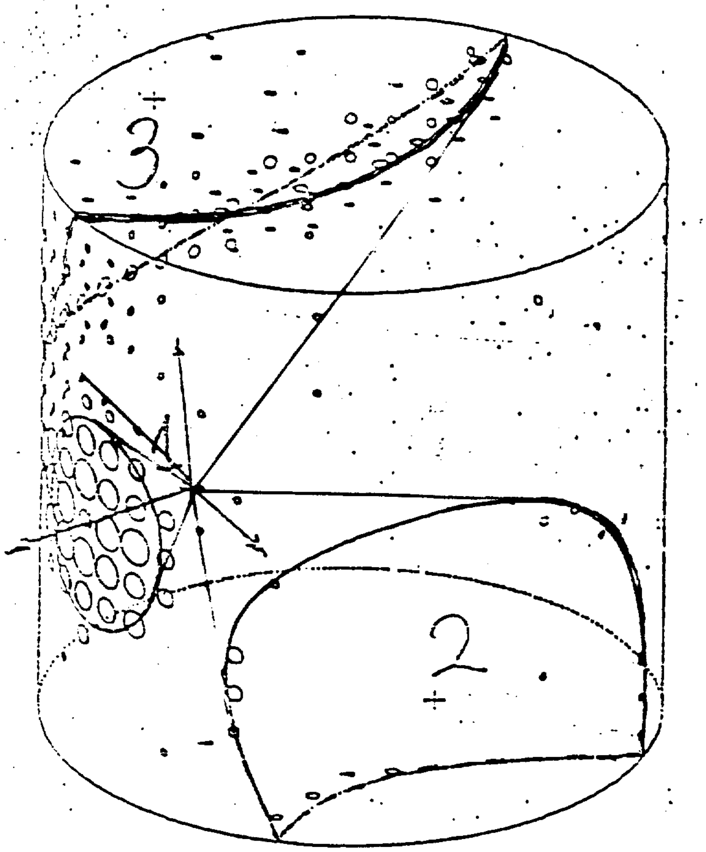
FIDUCIAL MASS : 780 tonnes
(NUCLEON DECAY)

FIDUCIAL MASS : 680 tonnes
(LOW ENERGY ν's)

~ 20% LIGHT COLLECTED

PHYSICS :

- LOW ENERGY ν's
  - ^8B SOLAR ν's
  - ν BURST FROM SN 1987 A
- NUCLEON DECAY & ATMOSPHERIC ν's
- COSMIC-RAY SOURCES
  - SINGLE μ's (Cyg. X3)
  - UPWARD-GOING μ's (SN 1987 A)



KAMIOKANDE II

WATER CHERENKOV DETECTOR

CHERENKOV LIGHT IN WATER : 42° CONES

948 PHOTO-MULTIPLIER TUBES ON THE WALLS

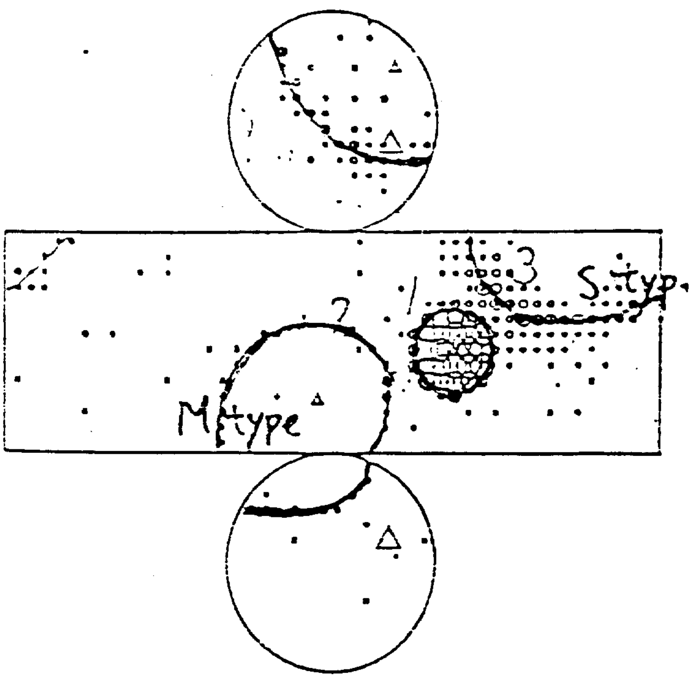
→ RING PATTERNS

SENSE OF TRACK DIRECTION

DISTINGUISH

S - TYPE : SHOWERING PARTICLES (e γ)

M - TYPE : NON SHOWERING PARTICLES (μ, π)



<u>TWO LARGE WATER CHERENKOV EXPERIMENTS</u> :

- I.M.B. Morton salt Mine, Ohio, USA
  8000 tonnes 1570 m.w.e.
- KAMIOKANDE : Kamioka Mine, Japan
  3000 tonnes 2700 m.w.e.

KAMIOKANDE II CHERENKOV DETECTOR

- **TRIGGER** :

  20 P.M.T's WITHIN 100 ns

  (LOW ENERGY ELECTRONS :

  THRESHOLD ~ 7.5 MeV)

  for muons : THRESH. ~ 165 MeV/c

- **MEASURED QUANTITIES** :

  - **CHARGE** COLLECTED BY EACH P.M.T.

    CHERENKOV RING PATTERN

    SHOWERING VS. NON SHOWERING

    e, γ μ π ... (> 1G...)

  - **TIMES** OF P.M.T. SIGNALS

    IMPROVES VERTEX RECONSTRUCTION

    Δx : 1 m → 20 TO 50 cm

    MULTI-RING EVENT   IF TIMING AVAILABLE

- **DELAYED SIGNALS** :

  UP TO 10 μs AFTER TRIGGER

  ELECTRONS FROM μ DECAY

  EFFICIENCY ($\mu \to e$ DECAY) 80% in KAMIOKANDE II   (OR $\pi \to \mu \to e$ DECAYS)

- **ENERGY RESOLUTION** :

  $$\Delta E / E \sim \frac{3.5\%}{\sqrt{E_{GeV}}}$$

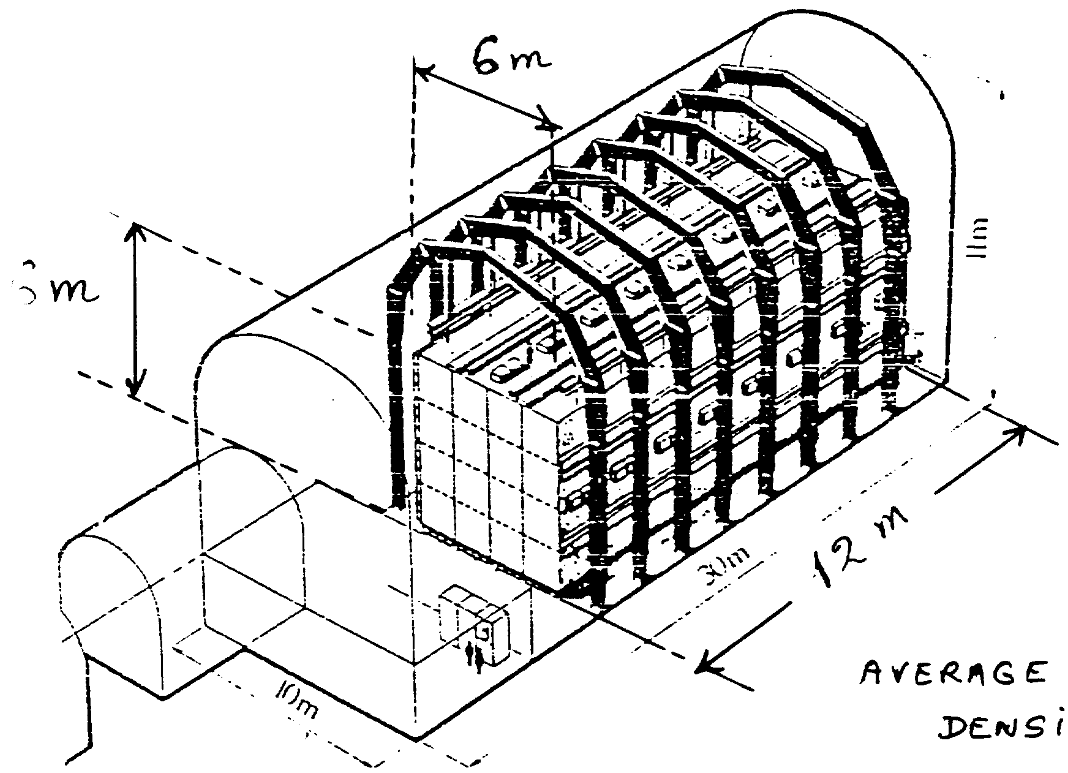
  22% AT 10 MeV

CALIBRATION : fast pulsed light sources.

At low energy : Cf-Ni γ source.

FRÉJUS TRACKING CALORIMETER

(FRÉJUS ALPINE ROAD TUNNEL, MODANE, FRANCE)
4800 [illegible]



AVERAGE DENSITY : 2

FINE GRAIN DETECTOR ...

Flash tubes 5mm x 5mm
(6 m long) Gas : Ne (70%) He (30%)
0.9 10^6 CHANNELS / 2 VIEWS

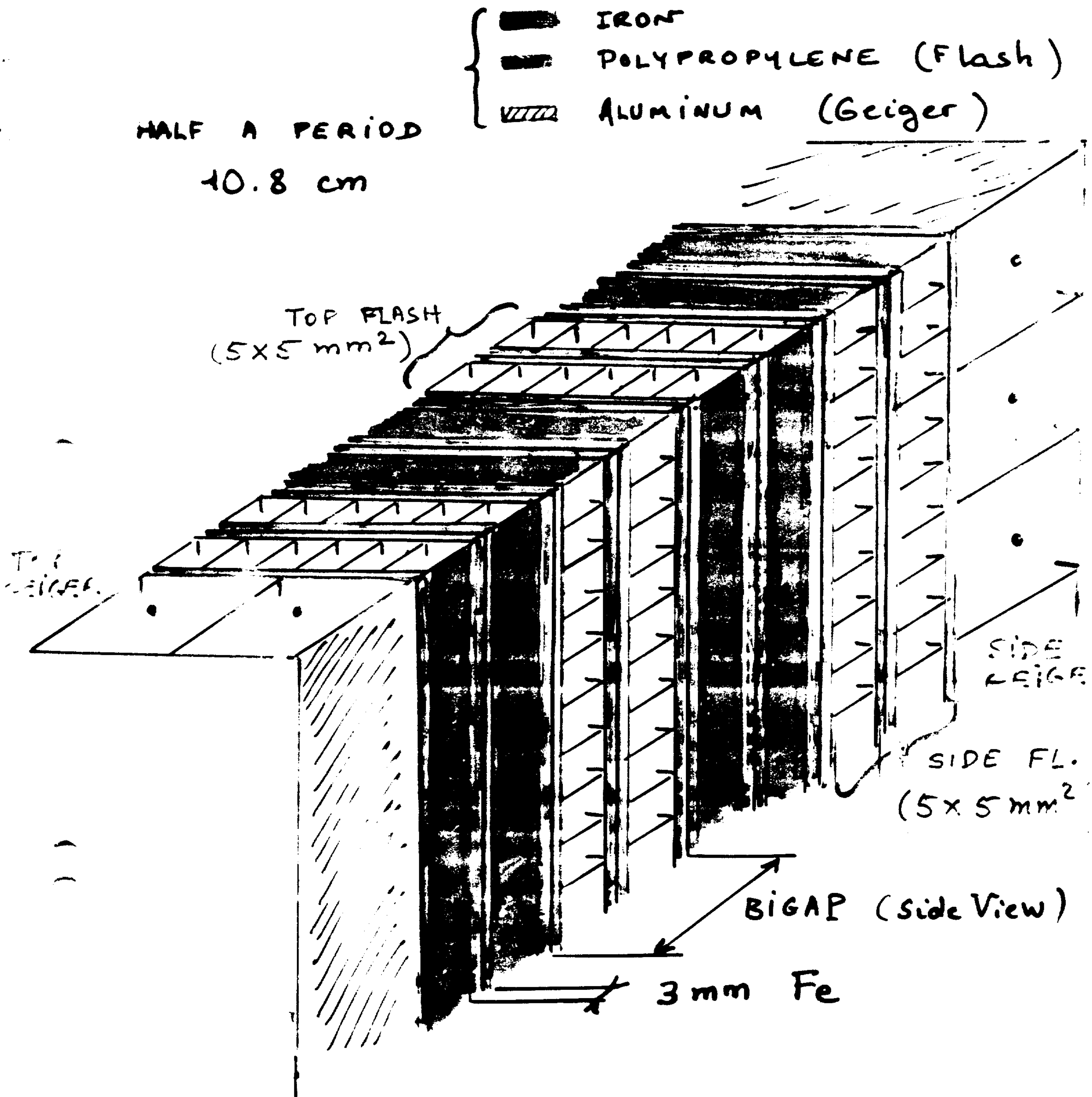
.. TRIGGERED BY 113 GEIGER PLANES
1 PLANE EVERY 11 cm
Gas Ar (98%)

TOTAL MASS : 912 tonnes
FIDUCIAL MASS : 550 tonnes

PHYSICS :

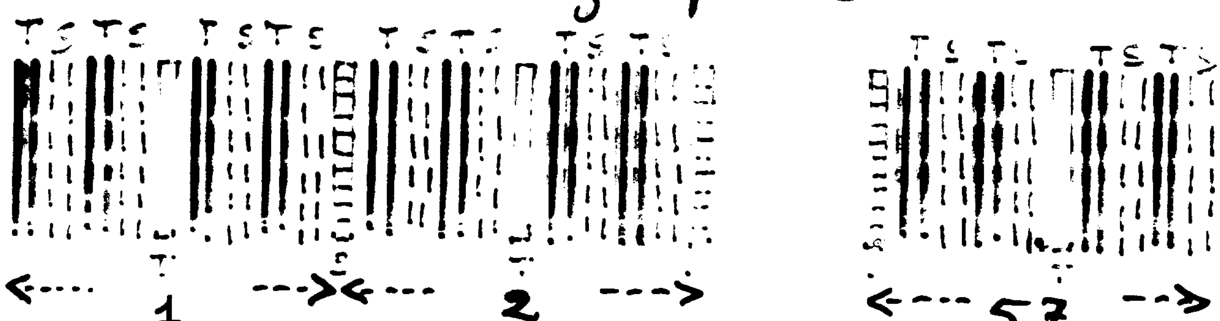
- NUCLEON DECAY & ATMOSPHERIC ν's
- COSMIC RAY SOURCES
  Cyg X3, SN 1987 A
- MUON BUNDLES
  Cosmic-ray composition

GENERAL STRUCTURE



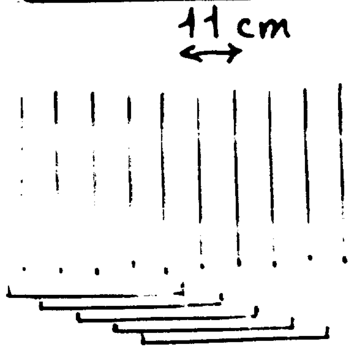
456 = 8 × 57 Flash Ch. [redacted]GAPS

113 Geiger planes



FRÉJUS FINE GRAIN TRACKING CALORIMETER

- **TRIGGER** : (GEIGER PLANES)



  - SUM UP CONTRIBUTIONS OF 5 CONSECUTIVE GEIGER PLANES : $N = \Sigma(C)$
  - "CONTRIBUTION" = NUMBER OF FIRED TUBES, LIMITED TO 3. MORE THAN 3 HITS COUNT FOR 3.
  - REQUIRE $N \geq 5$ WITHIN 300 ns

RATES : 20 COSMIC-RAY MUONS / h
20 RANDOM COINCIDENCES / h
(Radioactivity 2400 Hz / plane + electronic noise)

* Flash chamber dead time (4 s) not critical with these rates (4 % of the time)

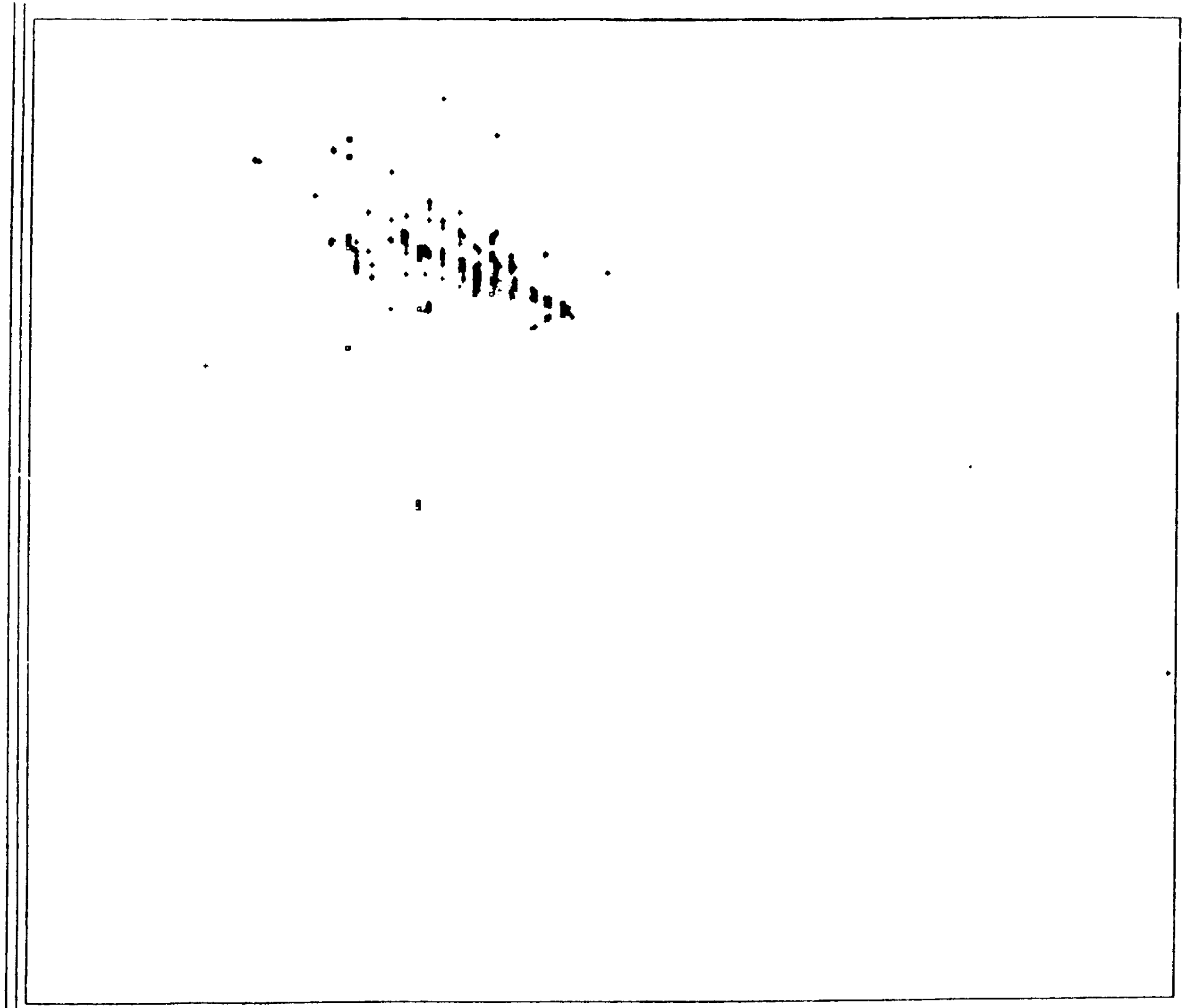
- **ENERGY RESOLUTION / THRESHOLDS**

$\frac{\Delta E}{E} \sim 11\%$ AT 1 GeV

Calibration : Structure exposed to e beam (DESY), π & μ beams (BON

Trigger threshold : [illegible] MeV

Visibility threshold : electrons, μ [illegible] MeV/c
proton 500 MeV/c



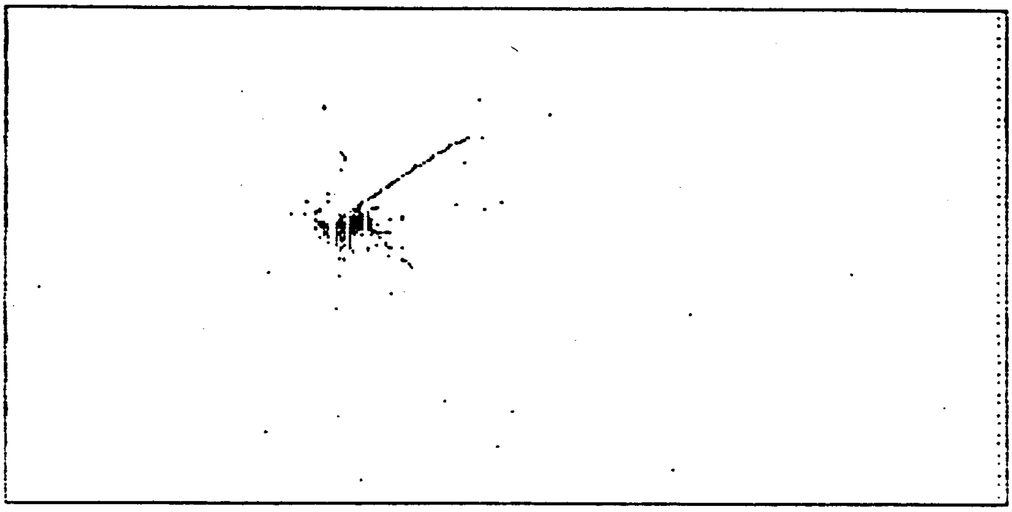
ν_e ($\bar{\nu}_e$) EVENT
TOP VIEW
(ZOOM)

oui
quelle vue?
1

ÉVÉNEMENT D (FRÉJUS)

SIDE VIEW

Screen : 1 713 F.Hits 50 G.Hits



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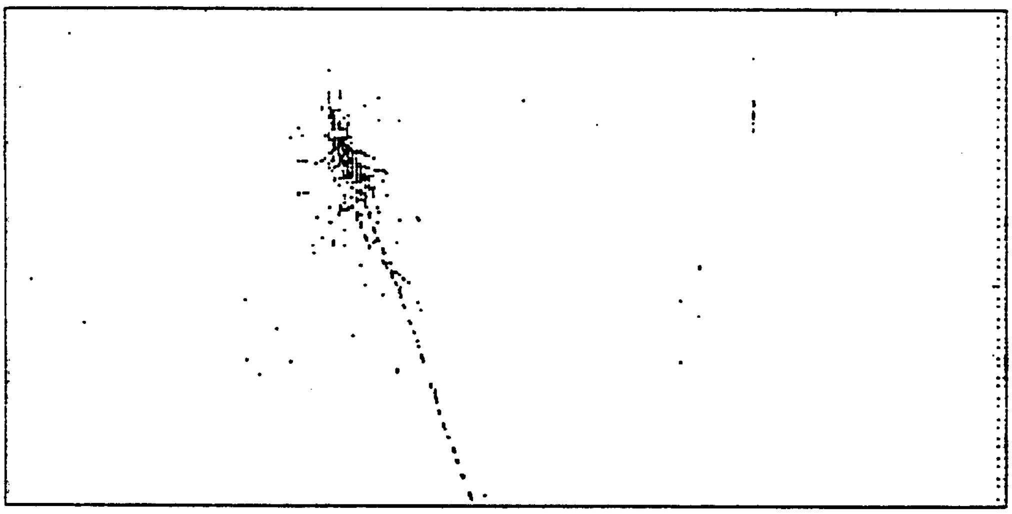
TOP VIEW

Screen : 1 F.Hits 1054 G.Hits 107



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2.3 NUCLEON DECAY : CHANNEL PER CHANNEL ANALYSIS

- DEFINE SELECTION CRITERIA FOR THE RELEVANT CHANNEL.

  1). RECONSTRUCT VERTEX.
  - REQUIRE VERTEX TO BELONG TO FID^{L} VOLUME
  - REQUIRE ALL TRACKS TO BE CONFINED IN DETECTOR. ("FULLY CONTAINED" EVENTS)

  2) TOPOLOGICAL CRITERIA
  - Number of rings / prongs
  - Showering vs. Non Showering
  - Possible $\mu \to e$ decay signal

  3) KINEMATICAL CRITERIA.
  - Modes with a charged lepton : ΣE_i, $|\Sigma \vec{p}_i|$, Total effective mass
  - Meson effective mass (e.g. $\gamma\gamma$ mass compatible with m_{π^0}).
  - Opening angle between tracks (e.g. $\gamma\gamma$ angle for $\eta^0 \to \gamma\gamma$)

  * $N \to \ell^{\pm}$ + meson more constrained
  $\Sigma E_i \simeq M$, $|\Sigma \vec{p}_i|$ IN FERMI MOMENTUM RANGE

  ... BUT NUCLEAR EFFECTS
  (FINAL STATE PARTICLES MAY INTERACT WITHIN TARGET NUCLEUS)

$$\Downarrow$$

SAMPLE OF EXP^{L} CANDIDATE(S)

- **SIMULATE THE RELEVANT DECAY MODE**

  1) "FINAL" STATE PARTICLES (after meson decays)

  2) NUCLEAR EFFECTS : final state HADRONS MAY INTERACT IN TARGET NUCLEUS
     elastic scattering : modify $|\Sigma \vec{p}_i|$
     charge exchange, absorption } modify topology
     * UNCERTAINTIES IN NUCLEAR MODEL
  3) HADRON SECONDARY INTERACTIONS IN THE DETECTOR → SECONDARY VERTEX
  4) DETECTOR RESPONSE
     NEEDS A GOOD MONITORING OF TRIGGER AND DETECTION EFFICIENCIES
  5) SCAN THE SIMULATED EVENTS, WITH THE SAME CRITERIA AS THE EXPERIM^L ONES (take account of possible misidentifications of main vertex or of final particles)

SAMPLE OF "MONTE-CARLO" N-DECAY EVENTS SATISFYING SELECTION CRITERIA.

⇓

OVERALL EFFICIENCY ε

- ESTIMATE THE BACKGROUND RATE OF ATMOSPHERIC NEUTRINOS.

1) CALCULATION OF THE NEUTRINO FLUX:
∼ 20% - 30% ACCURACY
Geomagnetic effects ← depend on site latitude
Solar modulation "

2) TWO POSSIBLE WAYS:

SIMULATION	DIRECT USE
BASED ON ACCELERATOR ν EXPERIMENTS	OF ACCELERATOR DATA (IF DETECTORS ARE SIMILAR)

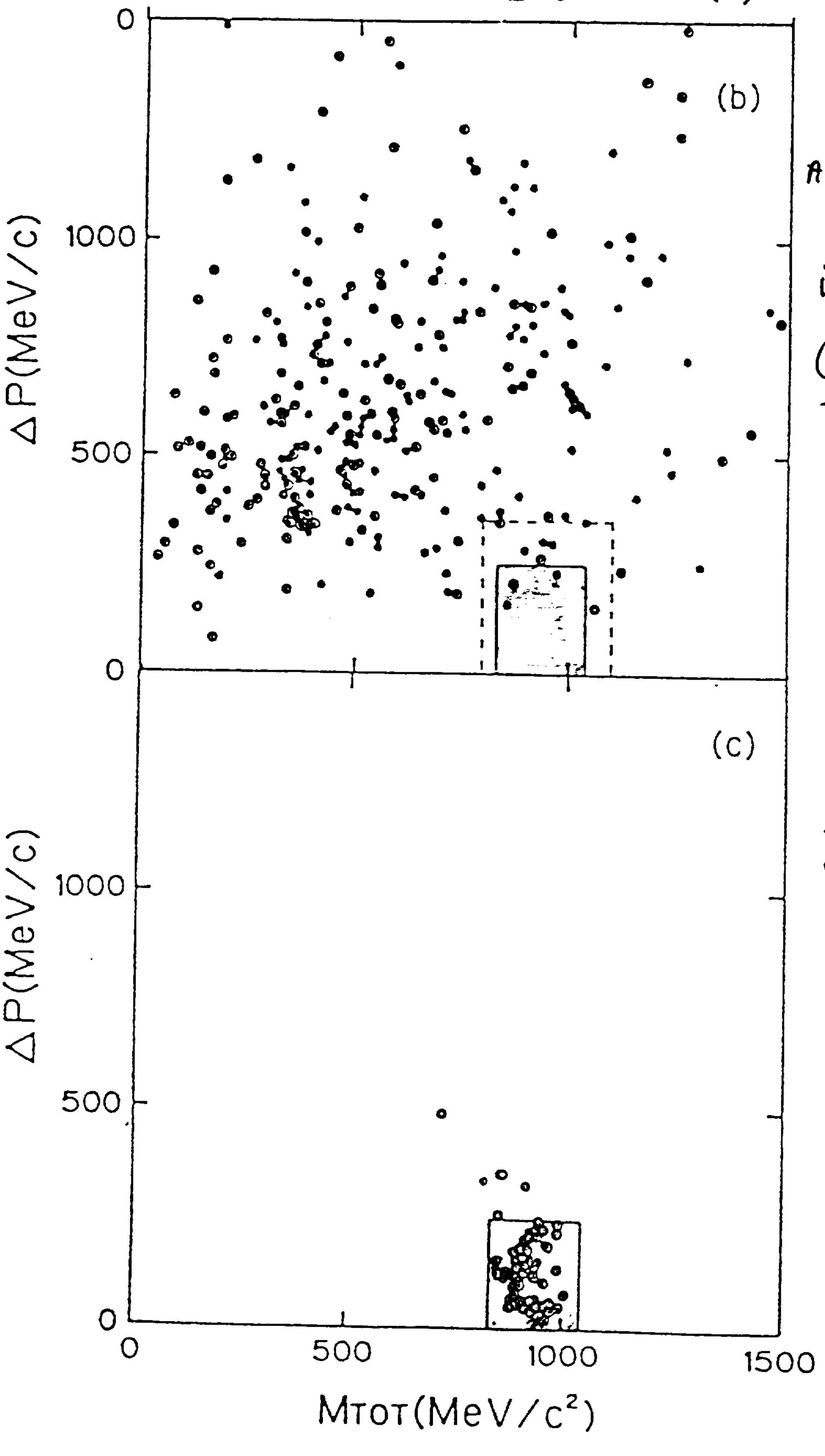
CERN PS / ANL / BNL

• NUCLEAR EFFECTS • SECONDARY INTER^{NS} • DETECTOR RESPONSE • SCAN AS NUCLEON DECAY CANDIDATES (detected protons interpreted as π/μ) IMB, KAMIOKANDE, FRÉJUS	• ANALYZE EVENTS AS N-DECAY CANDIDATE • WEIGHT EVENTS TO TAKE ACCOUNT OF { - DIFF^{CE} IN SPECTRA { - DETECTOR SIZE & POSITION / BEAM • CORRECT FOR ν_e's (very few in acceler^r beams) NUSEX, FRÉJUS FRÉJUS USED THE AACHEN - PADOVA EXP^T at CERN: 4000 ν_μ's, 1000 $\bar{\nu}_\mu$'s EQUIV^T TO 90 kilotonnes x years

BACKGROUND RATE PER kilotonne x year
R_B

MODES WITH A CHARGED LEPTON

"MONTE-CARLO" EVENTS ($\geq$ 2 RINGS)



ATMOSPHERIC ν $\bar{\nu}$ INTERACTIONS ($\equiv$ 11.4 kilotonnes x years)

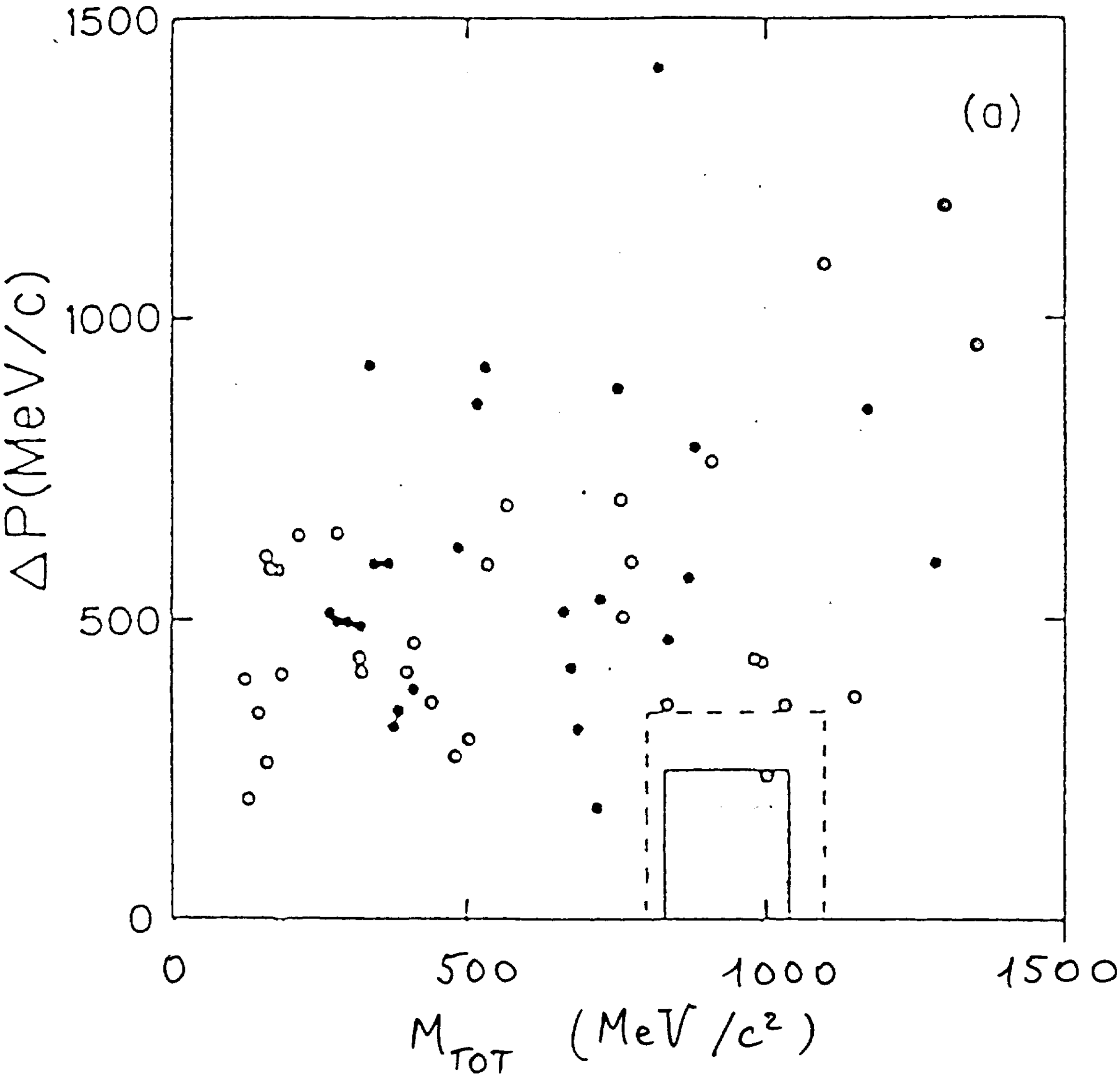
$p \to e^+\pi^0$

KAMICKANDE II : KINEMATICAL CRITERIA

KAMIOKANDE II

DATA SAMPLE : 2.46 kilotonnes x years

MULTI-RING EVENTS. (≥ 2 RINGS)

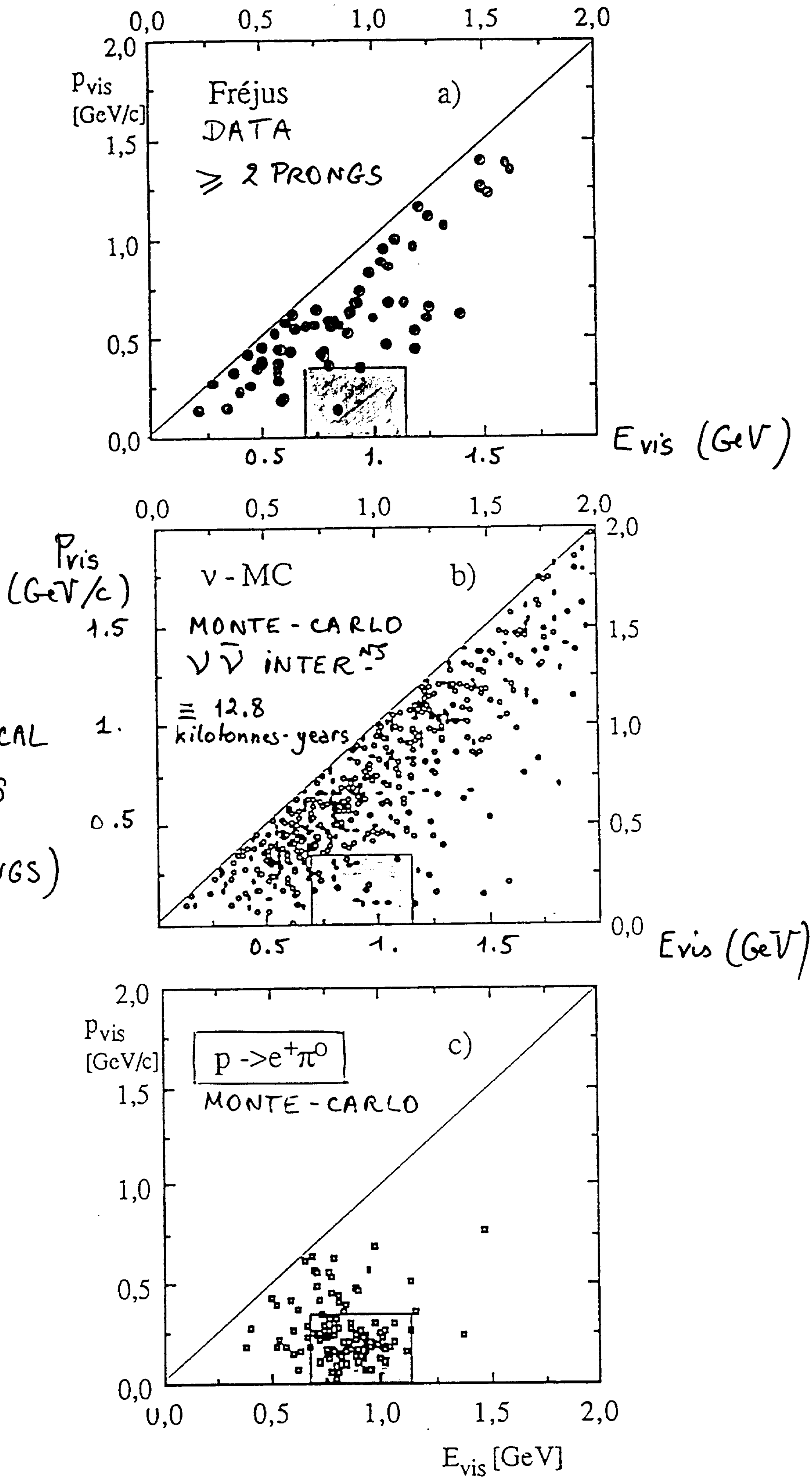


○ NO μ-DECAY

● AT LEAST ONE OBSERVED μ-DECAY

NUCLEON DECAY INTO CHARGED LEPTON + MESON

FRÉJUS KINEMATICAL ANALYSIS (≥ 2 PRONGS)



NUCLEON DECAY INTO $\bar{\nu}$ + MESONS

e.g. $p \to K^+ \bar{\nu}$

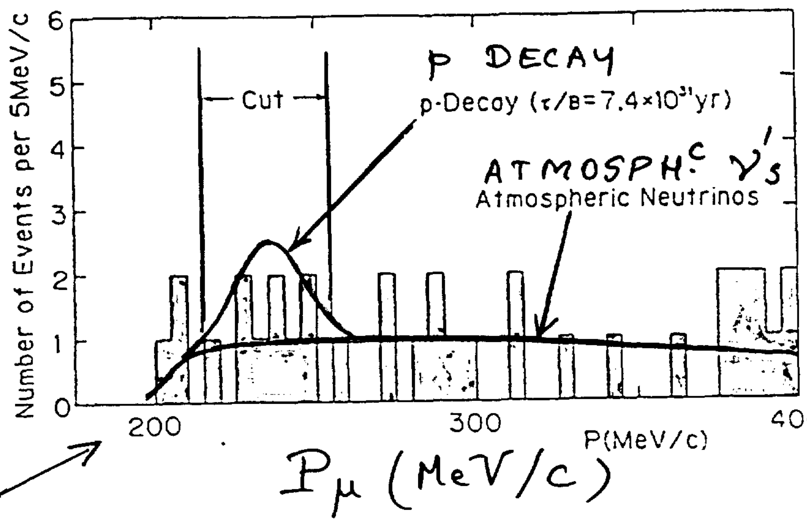
K^+ DECAYS AT REST $\longrightarrow$ MONO-ENERGETIC μ^+ ($P_\mu = 236$ MeV/c)

THEN $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

KAMIOKANDE II

K^+ NOT VISIBLE (below Cherenkov threshold)

- 1 RING
- MUON-LIKE
- μ - DECAY
- CUT IN P_μ ⟶



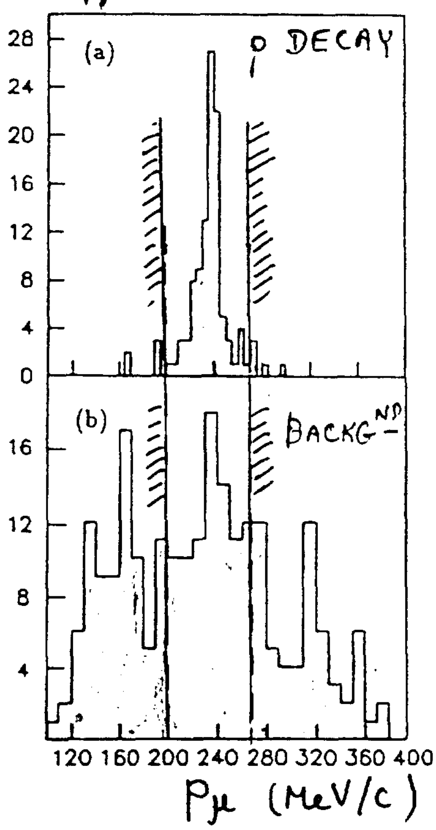
5 CANDIDATES
4.5 EXPECTED BACKG.ND EV.TS (2.46 kt × yr.)

FRÉJUS

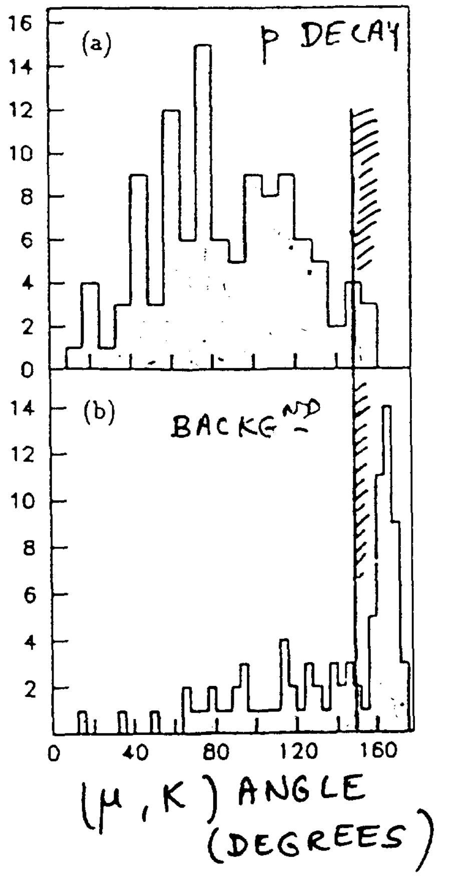
K^+ IS VISIBLE IN 30% OF SIMULATED $p \to \bar{\nu} K^+$ EV.TS

- 1 OR 2 "NON SHOWERING" PRONGS
- CUT IN P_μ ⟶ $200 \leq P_\mu \leq 270$ (MeV/c)
- CUT IN P_K: $300 \leq P_K \leq 500$ (MeV/c)
- CUT IN (μ, K) ANGLE

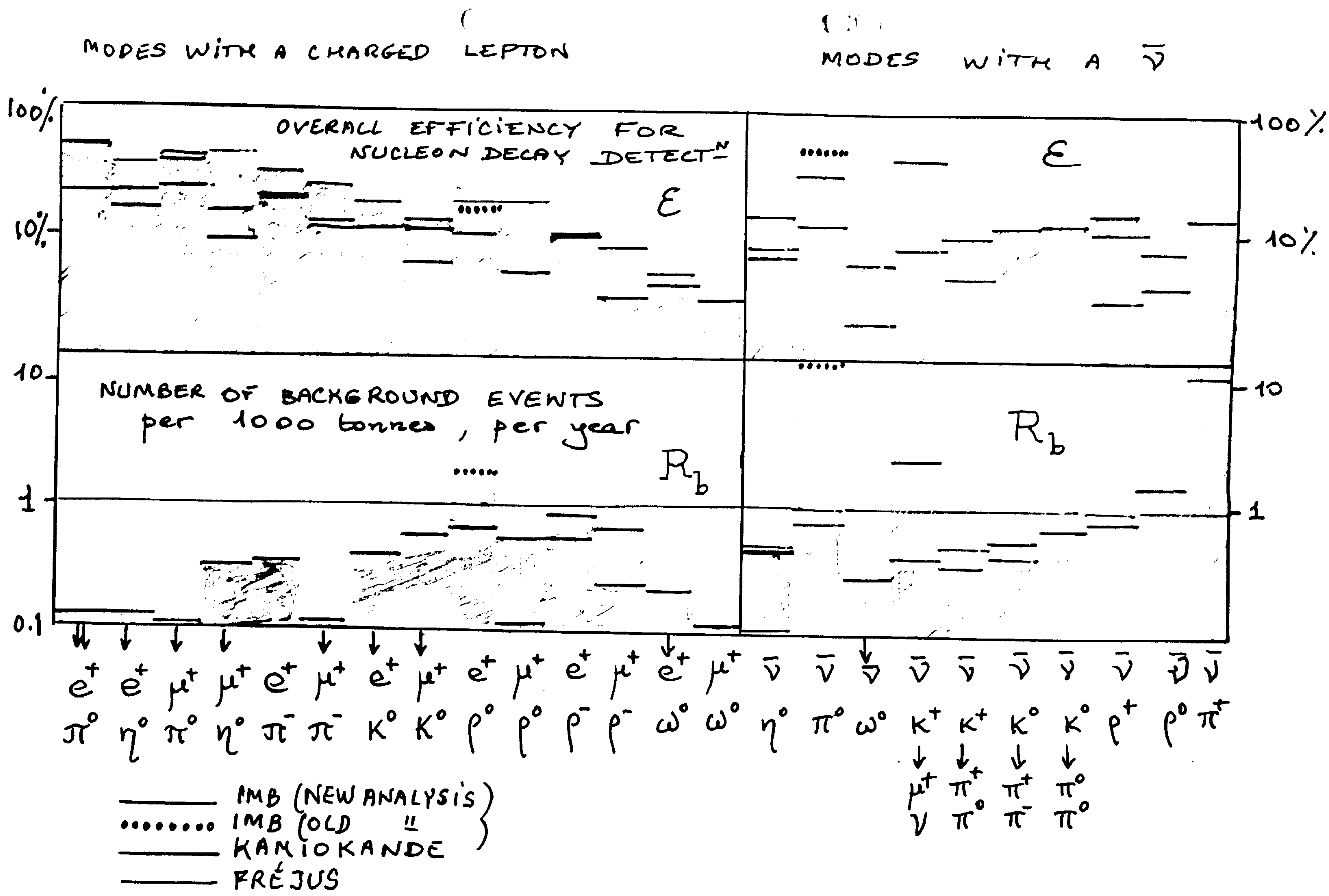
SIMULATED P_μ DISTRIBUTION

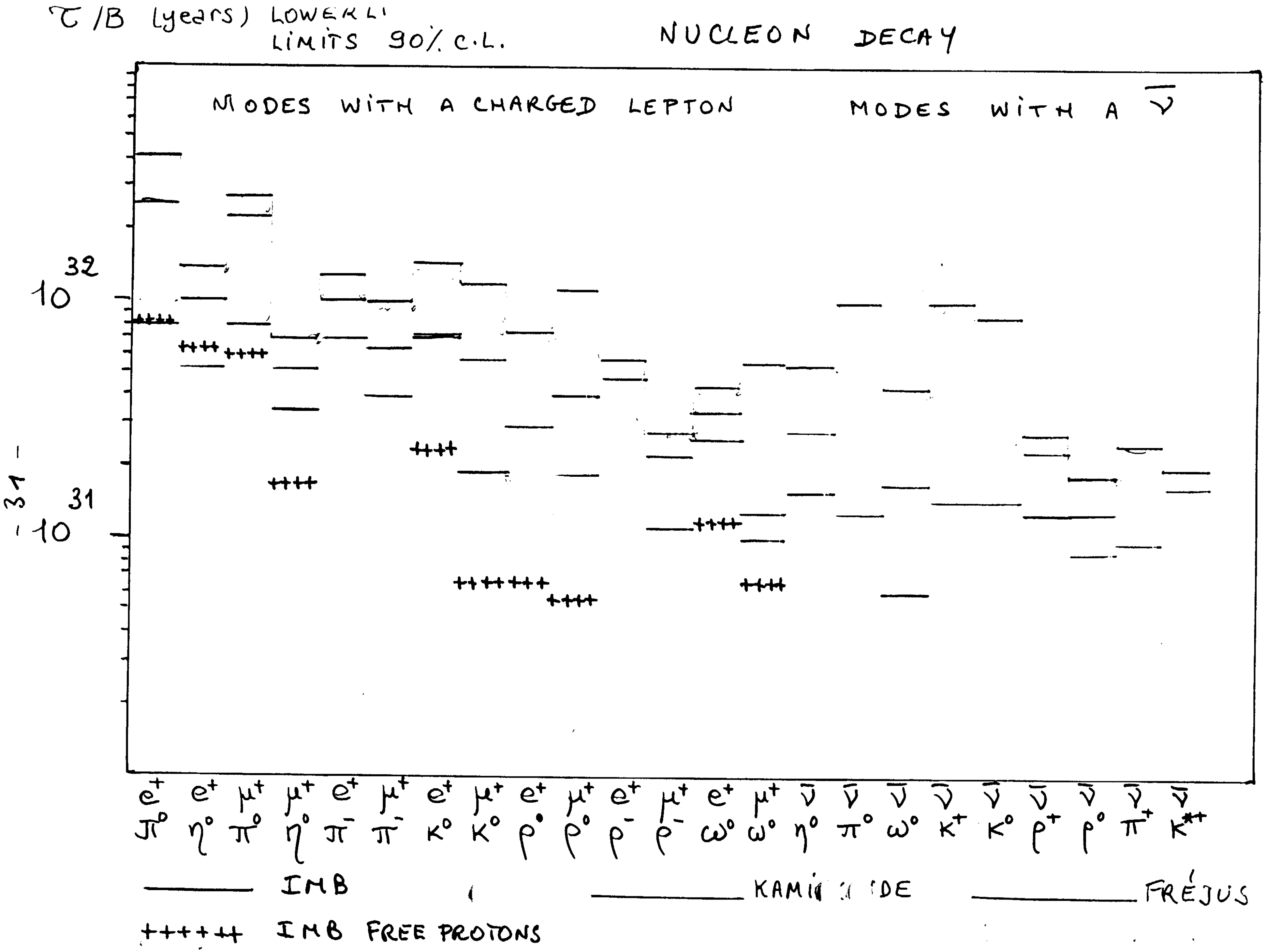


SIMULATED DIST.N FOR (μ, K) ANGLE



1 CANDIDATE
1 EXPECTED BACKG.ND EV.T


MODES WITH A CHARGED LEPTON
MODES WITH A $\bar{\nu}$
OVERALL EFFICIENCY FOR NUCLEON DECAY DETECT^N
ε
NUMBER OF BACKGROUND EVENTS per 1000 tonnes, per year
R_b
100%
10%
10
1
0.1
$e^+\pi^0$ $e^+\eta^0$ $\mu^+\pi^0$ $\mu^+\eta^0$ $e^+\pi^-$ $\mu^+\pi^-$ e^+K^0 μ^+K^0 $e^+\rho^0$ $\mu^+\rho^0$ $e^+\rho^-$ $\mu^+\rho^-$ $e^+\omega^0$ $\mu^+\omega^0$
$\bar{\nu}\eta^0$ $\bar{\nu}\pi^0$ $\bar{\nu}\omega^0$ $\bar{\nu}K^+$ $\bar{\nu}K^+$ $\bar{\nu}K^0$ $\bar{\nu}K^0$ $\bar{\nu}\rho^+$ $\bar{\nu}\rho^0$ $\bar{\nu}\pi^+$
$\mu^+\nu$ $\pi^+\pi^0$ $\pi^+\pi^-$ $\pi^0\pi^0$
IMB (NEW ANALYSIS)
IMB (OLD ")
KAMIOKANDE
FRÉJUS


τ/B (years) LOWER LIMITS 90% C.L.
NUCLEON DECAY
MODES WITH A CHARGED LEPTON
MODES WITH A $\bar{\nu}$
10^{32}
10^{31}
$e^+ \pi^0$
$e^+ \eta^0$
$\mu^+ \pi^0$
$\mu^+ \eta^0$
$e^+ \pi^-$
$\mu^+ \pi^-$
$e^+ K^0$
$\mu^+ K^0$
$e^+ \rho^0$
$\mu^+ \rho^0$
$e^+ \rho^-$
$\mu^+ \rho^-$
$e^+ \omega^0$
$\mu^+ \omega^0$
$\bar{\nu} \eta^0$
$\bar{\nu} \pi^0$
$\bar{\nu} \omega^0$
$\bar{\nu} K^+$
$\bar{\nu} K^0$
$\bar{\nu} \rho^+$
$\bar{\nu} \rho^0$
$\bar{\nu} \pi^+$
$\bar{\nu} K^{*+}$
——— IMB
——— KAMIOKANDE
——— FRÉJUS
++++++ IMB FREE PROTONS

2.4 NUCLEON DECAY : PRESENT RESULTS

- BACKGROUD - FREE MODES : NO CANDIDATE !

τ/B BEYOND 10^{32} YEARS.

τ/B	$p \to e^+\pi^0$	$p \to e^+\eta^0$	$p \to \mu^+\pi^0$
IMB	> 3.1	> 1.0	> 2.7
KAMIOKA	> 2.6	> 1.4	> 2.3
FRÉJUS	> 0.8	> 0.52	> 0.79

LIMITS IN 10^{32} YEARS

- OTHER MODES WITH A CHARGED LEPTON.

  BACKGROUND AND CANDIDATES AT THE LEVEL OF 0.5 – 1. EVTS / (kilotonne × year)

  τ/B LIMITS CLOSE TO 10^{32} years.

- MODES WITH A FINAL $\bar{\nu}$.

  τ/B LIMITS ~ SOME 10^{31} years

  * KAMIOKANDE CAN ACHIEVE BETTER LIMITS IN SOME MODES :

  e.g. $\boxed{p \to \bar{\nu} K^+}$ $\tau/B > 10^{32}$ YEARS

  (favoured by supersymmetric theories)

3. NEUTRON - ANTINEUTRON OSCILLATIONS

3.1 GENERAL FEATURES

IN THE $\{|n\rangle, |\bar{n}\rangle\}$ REPRESENTATION, THE HAMILTONIAN IS

$$H = \begin{pmatrix} M + V_1 & \delta \\ \delta & M + V_2 \end{pmatrix}$$

- POTENTIAL ENERGIES DUE TO :
  - n INTERACTIONS : V_1
  - $\bar{n}$ INTERACTIONS : V_2

  } MAGNETIC FIELD OR NUCLEAR POTENTIAL

- δ RESPONSIBLE FOR OSCILLATIONS

EXPERIMENTS SHOULD GIVE LOWER BOUNDS ON :

$$\tau_{osc.} = \frac{1}{\delta}$$

BUT $\delta \ll \Delta V \qquad \left(\Delta V = \frac{V_1 - V_2}{2}\right)$

ENERGY EIGENSTATES :

$$E = M + \frac{V_1 + V_2}{2} \pm \sqrt{\Delta V^2 + \delta^2}$$

$n \to \bar{n}$ CONVERSION PROBABILITY AT TIME t :

$$P_{n\to\bar{n}}(t) = \frac{\delta^2}{\Delta V^2 + \delta^2} \sin^2\left(\sqrt{\Delta V^2 + \delta^2}\; t\right)$$

$$\boxed{P_{n\to\bar{n}}(t) = \frac{\delta^2}{\Delta V^2+\delta^2}\sin^2\left(\sqrt{\Delta V^2+\delta^2}\; t\right)}$$

$$\tau_{osc.} = \frac{1}{\delta}$$

TWO EXPERIMENTAL APPROACHES

FREE NEUTRONS FROM A REACTOR (HIGH FLUX REACTOR) DIRECT	BOUND NEUTRONS $n \to \bar{n}$ IN A NUCLEUS $\Rightarrow$ ANNIHILATION (NUCLEON DECAY EXPT.) NUCLEAR MODEL

A - "FREE" NEUTRONS FROM A REACTOR

"FREE" MEANS THAT $\Delta V \cdot t_f \ll 1$ (t_f: n TIME OF FLIGHT)

(IN ANY CASE $t_f \ll n$ LIFETIME $(\sim 10^3 s)$)

THUS $\boxed{P_{n\to\bar{n}}(t) \simeq \delta^2 t_f^2 = \frac{t_f^2}{\tau_{osc.}^2}}$

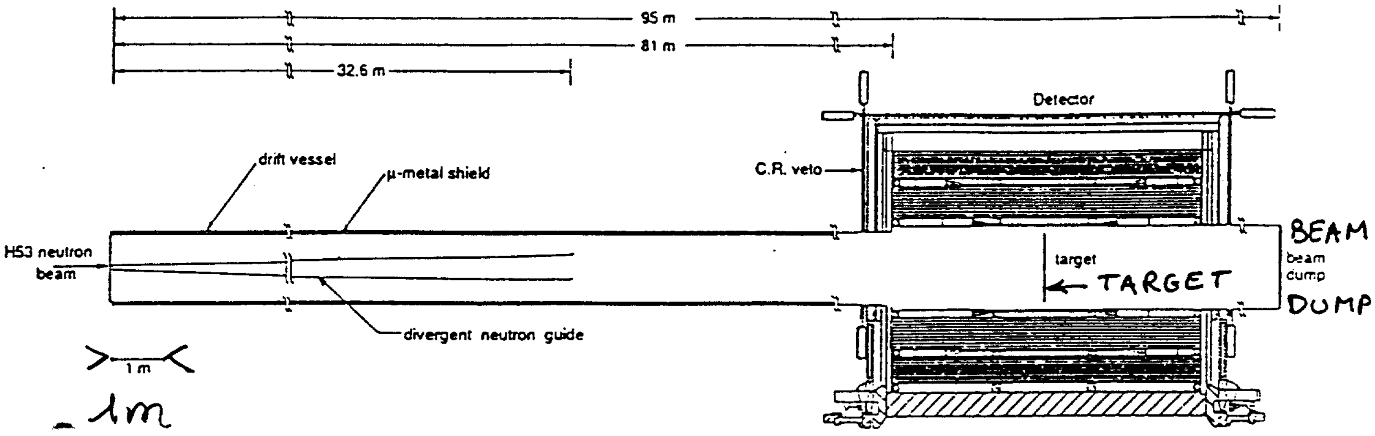
* BUT SHIELD AGAINST EARTH MAGNETIC FIELD NEEDED :

$$\Delta V \sim \mu_n B \ll \frac{1}{t_f}$$

OR $$B \ll \frac{10^{-8}\,\text{Tesla}}{(t_f / 1s)}$$

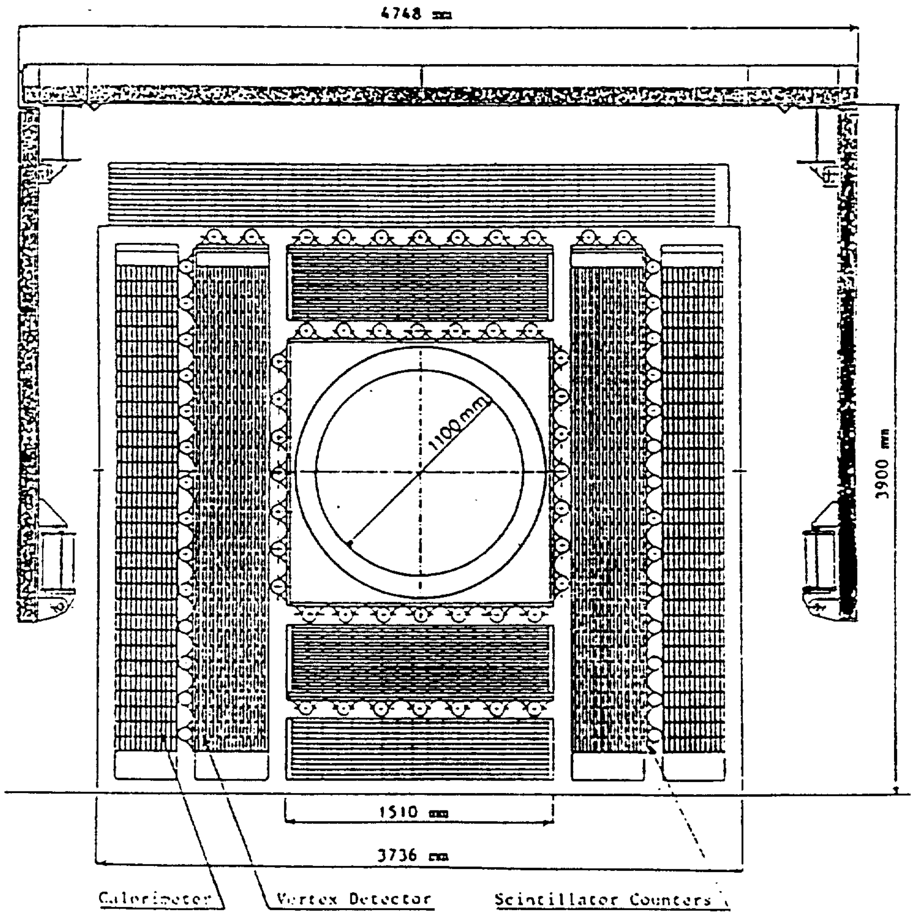
* ADVANTAGE : MONITOR BACKGROUND BY SWITCHING ON A SMALL MAGNETIC FIELD. (SUPPRESS OSCIL.)

HEIDELBERG, ILL, PADOVA, PAVIA Phys. Lett. B236 (1990) 95



a

ANNIHILATION DETECTOR



b

B. BOUND NEUTRONS : $n \to \bar{n}$ IN A NUCLEUS.

NUCLEON DECAY EXPERIMENTS.

SEARCH FOR "NUCLEON-DECAY-LIKE" EVENTS WITH TOTAL ENERGY $= 2M$.

NUCLEAR POTENTIALS : $\begin{cases} n : & V \\ \bar{n} : & \bar{V} - i\dfrac{\Gamma_a}{2} \end{cases}$

ABSORPTIVE PART : ACCOUNTS FOR $\bar{n}$ ANNIHIL^N IN NUCLEAR MATTER.

$$\delta = \frac{1}{\tau_{osc.}} \ll \begin{cases} V - \bar{V} \\ \Gamma_a \end{cases}$$

ENERGY EIGENVALUE (STATE CLOSEST TO $|n\rangle$)

$$E = M + V + \frac{\delta^2 (V-\bar{V})}{(V-\bar{V})^2 + \frac{\Gamma_a^2}{4}} - \frac{i \frac{\Gamma_a}{2} \delta^2}{(V-\bar{V})^2 + \frac{\Gamma_a^2}{4}}$$

IMAGINARY PART IN E $\to \dfrac{1}{2\,\tau_{ANN.}}$

$$\frac{1}{\tau_{ANN.}} = \frac{\Gamma_a \delta^2}{(V-\bar{V})^2 + \Gamma_a^2/4}$$

RELATE $\tau_{osc.} = \dfrac{1}{\delta}$ WITH $\tau_{ANN.}$:

$$\boxed{\tau_{osc.} = \sqrt{\tau_{ANN.} \cdot t_R}}$$

GENERAL

WITH $t_R = \dfrac{\Gamma_a}{(V-\bar{V})^2 + \Gamma_a^2/4}$

MODEL-DEPENDENT

- CHERENKOV EXP^{TS} : ^{16}O $\quad t_R \simeq 10^{-23}\,s$
- TRACKING CALORIM^{RS} : ^{56}Fe $\quad t_R = 0.7\ 10^{-23}\,s$

3.2 EXPERIMENTS ON $n\bar{n}$ OSCILLATIONS

90% C.L.

"FREE" NEUTRONS EXPTS

REACTOR	EXPERIMT	NEUTRON FLUX s^{-1}	FREE FLIGHT LENGTH m	TIME OF FLIGHT $\sqrt{\langle t^2 \rangle}$ s	RESIDUAL MAGNETIC FIELD nT	DETECTOR	LOWER LIMIT ON $\tau_{osc.}$ (10^6 s)
I.L.L.	CERN, ILL, PADOVA, RUTHERFORD, SUSSEX	$1.5\ 10^{9}$	2.7	$2.6\ 10^{-3}$	< 100	STREAMER TUBES + 5 mm PLATES (Al, Fe)	1.
PAVIA	PAVIA ROMA	$3.2\ 10^{10}$	18.5	$8\ 10^{-3}$	810 ± 440	FLASH CHAMBERS Pb Fe PLATES	0.47
I.L.L.	HEIDELBERG ILL PADOVA PAVIA	$2.\ 10^{11}$	64	0.1	< 10	STREAMER TUBES + 1 & 2 mm PLATES (Fe)	10.

NUCL. DECAY

EXPERIMENT		$\tau_{ANN.}$ (years)	LOWER LIMIT $\tau_{OSC.}$ (10^6 s)
I.M.B.	^{16}O	$> 2.4\ 10^{31}$	88
KAMIOKANDE	^{16}O	$> 4.3\ 10^{31}$	120
FRÉJUS	^{56}Fe	$> 6.5\ 10^{31}$	120

SEARCH FOR BARYON NUMBER VIOLATION.

PROSPECTS.

1. NUCLEON DECAY

- ONE FUTURE EXPERIMENT : SUPERKAMIOKANDE.

  - TOTAL MASS : 50 000 tonnes
  - INNER MASS : 32 000 "
  - FIDUCIAL MASS : 22 000 "

  11.200 20"- PHOTOTUBES . LIGHT COLLECT^N 40%
  (+700 IN ANTI-COUNTER)

  Expected sensitivity : τ/B up to

$p \to e^+ \pi^0$	10^{34}	years
$p \to \mu^+ K^0$	3×10^{33}	"
$p \to \bar{\nu} K^+$	10^{33}	"

  EXPERIMENT IS EXPECTED TO BE FUNDED WITHIN 2 YEARS.

- DUE TO THE HIGH BACKGROUND REJECTION ACHIEVED IN SUCH AN EXPERIMENT, A VERY ACCURATE KNOWLEDGE OF ν INTERACTIONS WILL BE NEEDED: ν RUNS AT ACCELERATORS OF $\gtrsim 10^5$ ν INTERACTIONS ...

2. NEUTRON-ANTINEUTRON OSCILLATIONS

- BEST LIMITS ON $\tau_{osc.}$ ARE GIVEN BY NUCLEON DECAY EXPTS: $\tau_{osc.} > 1.2\ 10^8$ s. (90% C.L.)
  BUT SOME ASSUMPTIONS (nuclear model).

- FREE NEUTRON (DIRECT) EXPERIMENTS ARE ONLY ONE ORDER OF MAGNITUDE BELOW.