

LECTURE 3

SOLAR AUD SUPERNOVA NEUTRINOS

TO SEE INTO THE HEART OF A STAR VIA ITS NEUTRINO

PRODUCTION WE MUST HIDE THE DETECTOR UNDERGROUND TO
ESCAPE OTHER COSMIC RAYS.

AN ATTEMPT TO DETECT THE NEUTRINO

Ref 52

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[Communicated by MR P. M. S. BLACKETT]

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Fig 50

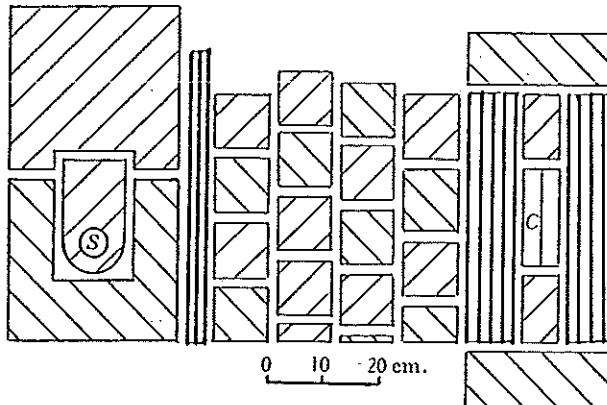


Fig. 1. First arrangement. *S*, source; *C*, counter.

PROC. CAMB. PHIL. SOC.

31, 99 (1935)

NO γ 's,

BUT $\mu \sim 10^{-3} \mu_e$

I. SOLAR NEUTRINOS

NEUTRINOS ARE PRODUCED IN 5 DIFFERENT STAGES OF THE
HYDROGEN BURNING CYCLE (AS

WELL AS IN THE C-N-O CYCLE) IN
(TABLE 5 AND FIG

THE SUN. DIRECT DETECTION

OF THESE NEUTRINOS SHOULD

CONFIRM OUR UNDERSTANDING

OF ONE OF THE MOST BASIC

ASTROPHYSICAL PROCESSES.

Table 5. Energy-producing nuclear reactions in the sun. (53)

Cycle and abundance	Reaction	$E(\nu)$ (MeV)
PPI 88%	$p + p \rightarrow d + e^+ + \nu_1$ (99.75%) $p + e^- + p \rightarrow d + \nu_2$ (0.25%) $d + p \rightarrow {}^3\text{He} + \gamma$ ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$	0 to 0.42 1.44
PPII 12%	${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$ $e^- + {}^7\text{Be} \rightarrow {}^7\text{Li} + \nu_3$ ${}^7\text{Li} + p \rightarrow 2 {}^4\text{He}$	0.86 (90%), 0.38 (10%)
PPIII 0.01%	${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$ ${}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_4$ ${}^8\text{Be} \rightarrow 2 {}^4\text{He}$	0 to 14.1
CNO	${}^{12}\text{C} + p \rightarrow {}^{13}\text{N} + \gamma$ ${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu_5$ ${}^{13}\text{C} + p \rightarrow {}^{14}\text{N} + \gamma$ ${}^{14}\text{N} + p \rightarrow {}^{15}\text{O} + \gamma$ ${}^{15}\text{O} \rightarrow {}^{15}\text{N} + e^+ + \nu_6$ ${}^{15}\text{N} + p \rightarrow {}^{12}\text{C} + {}^4\text{He}$	0 to 1.20 0 to 1.73

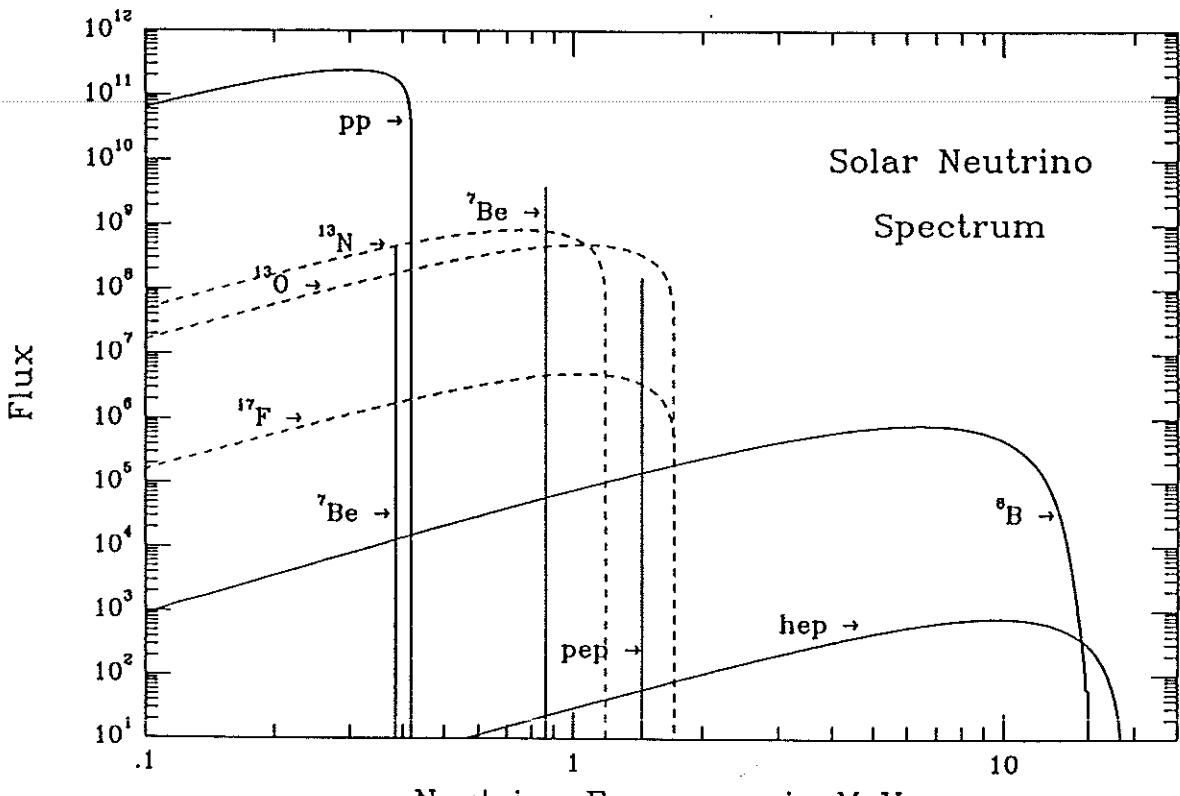


FIG 51 ref 54

Neutrino Energy, q , in MeV

NEUTRINO-NUCLEUS ABSORPTION CROSS SECTIONS RISE RAPIDLY

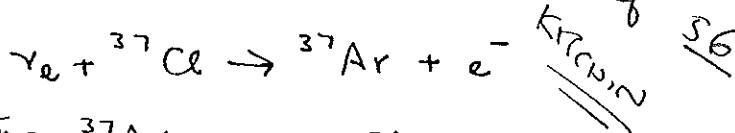
WITH ENERGY, SO THE MOST ACCESSIBLE NEUTRINOS ARE THE

THE 3-BODY DECAY ${}^8\text{B} \rightarrow 2\alpha + e^+ + \nu_e$, $\nu_e \text{ MAX} = 14.1 \text{ MeV}$.

A. THE HOME STATE ${}^{37}\text{Cl}$ EXPERIMENT

THIS ASTROCHEMICAL EXPERIMENT HAS BEEN IN OPERATION FOR 20 YEARS NOW, 4200 m (WATER EQUIVALENT) UNDERNEATH THE TOWN OF LEAD, SOUTH DAKOTA. THE DETECTOR CONSISTS OF 615 TONS OF C_2Cl_4 .

THE REACTION IS



THE ${}^{37}\text{Ar}$ DECAYS BACK TO

${}^{37}\text{Cl}$ WITH A HALF LIFE OF

37 DAYS. THE SIGNATURE OF

THIS DECAY IS A 2.8 KEV X-RAY

(IF K-CAPTURE).

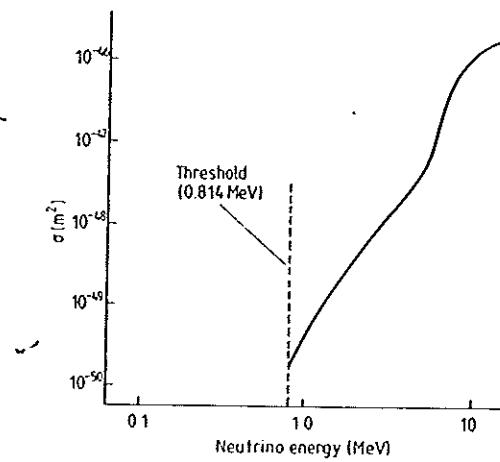


Figure 1.5.1 Neutrino absorption cross sections for the ${}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar}$ reaction.

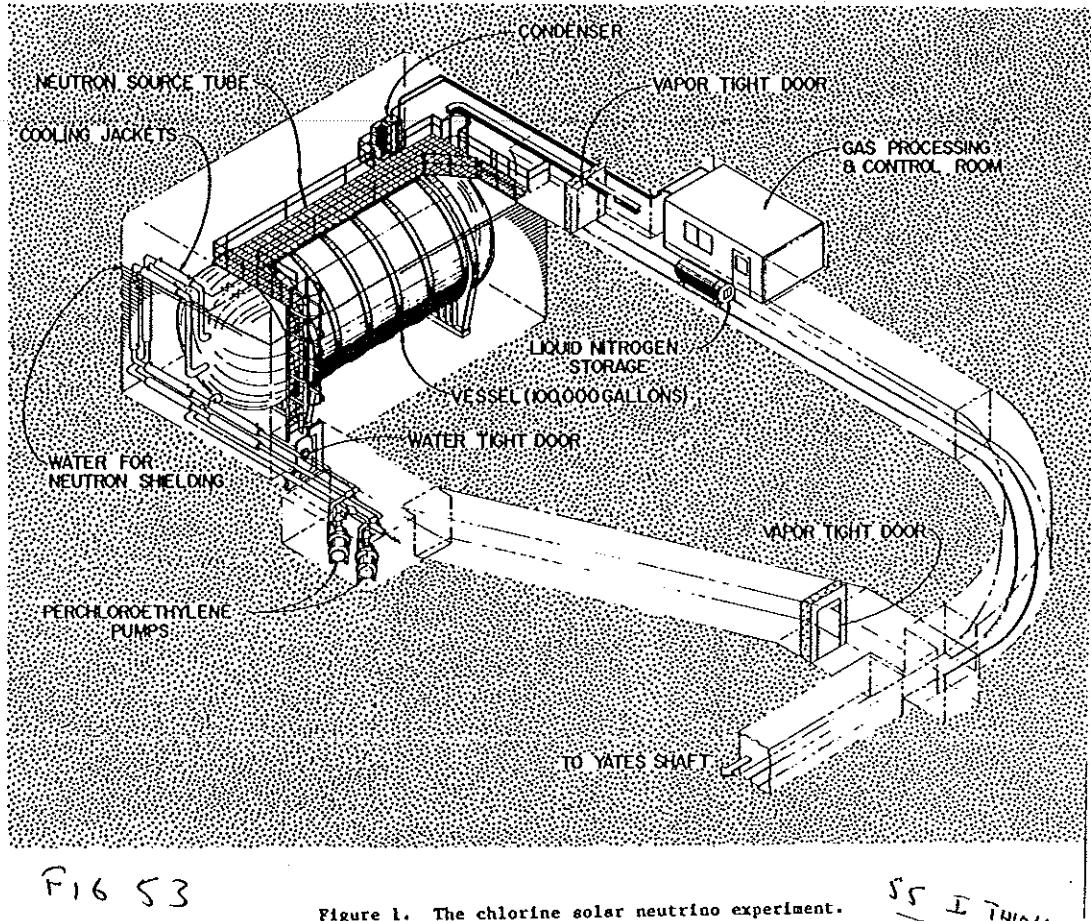


FIG 53

Figure 1. The chlorine solar neutrino experiment.

55 I THINK

EVERY 50 DAYS THE ^{37}Ar IS COLLECTED BY BUBBLING

He THRU THE TANK, AND CONDENSING THE Ar ON CHARCOL

AT LIQUID-NITROGEN TEMPERATURE. THE ARGON IS THEN BOILED

OFF THE CHARCOL AND ADDED TO THE GAS OF A SMALL PROPORTIONAL

COUNTER, WHICH WATCHES FOR THE 2.8 KeV X-RAY FROM ^{37}Ar DECAY.

ABOUT 10 COUNTS ARE

OBSERVED PER 50-DAY RUN,

FOR A TOTAL OF 774

DURING 1970-1984.

Fig 54
Run 1984

54
54

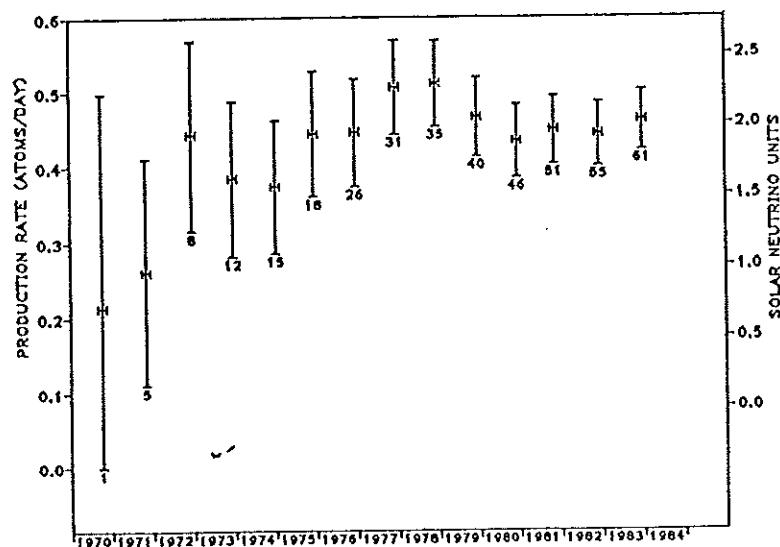


Figure 3. Experimental combined production rate beginning with Run 18 as a function of time. The number beneath each point shows the number of runs combined to give the production rate represented by that point.

ON CORRECTING FOR THE ^{37}Ar HALF LIFE, THE PRODUCTION RATE OF ^{37}Ar ATOMS IS MEASURED AS 0.38 ± 0.05 /DAY (AFTER SUBTRACTING A BACKGROUND OF 0.08 ± 0.03 /DAY).

BUT, THE CURRENT MODEL CALCULATION (BANCALL & ULRICH, 1987) IS 1.8 ± 0.6 ^{37}Ar /DAY.

THIS IS THE SOLAR NEUTRINO PROBLEM.

IS IT A DETECTOR PROBLEM, A NEUTRINO-PHYSICS PROBLEM, OR A SOLAR-PHYSICS PROBLEM?

THE EXPERIMENT IS A REAL EXPERIMENT, WITH CROSS CHECKS AND A LONG HISTORY OF CONSISTENCY. FURTHER KUNNING WILL CHANGE THE SITUATION VERY LITTLE. KNOWN AMOUNTS OF ^{37}Ar HAVE BEEN INJECTED IN THE C_2Cl_4 TANK AND SUCCESSFULLY RECOVERED.

SMALL AMOUNTS OF NATURAL ARGON ARE ADDED AT THE BEGINNING

Fig 55

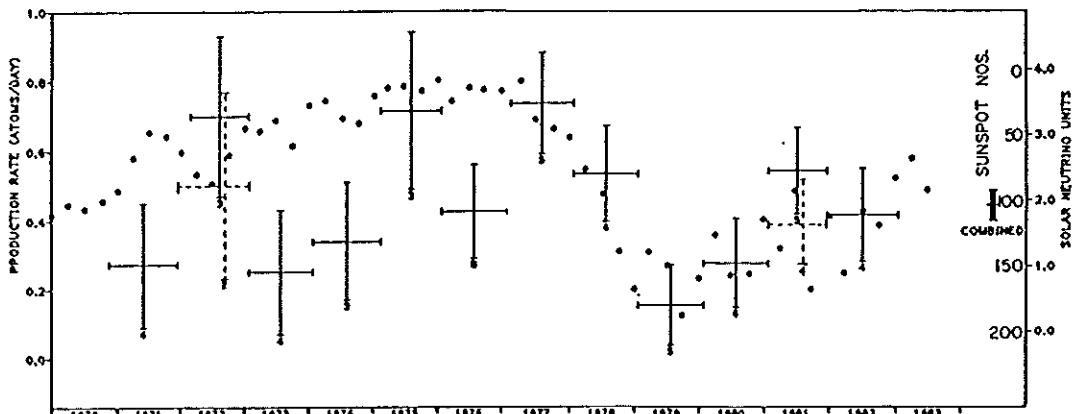


Fig. 6 (above). Yearly average results for the chlorine experiment superposed on monthly mean sunspot numbers (plotted inverted). The number of experimental runs included in the average is indicated for each year. The averages for 1972 and 1981 shown with dotted lines are without Runs 27 and 71, the runs that appear to correlate with the large solar flares of Aug. 4-8, 1971 and of Oct. 12, 1981.

Fig 56 ref 58

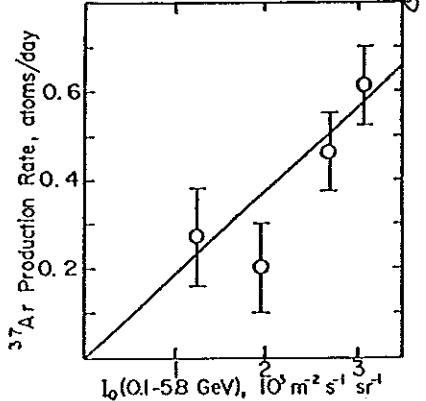


Fig. 7 (at right). The ^{37}Ar production rate divided into four bins according to the intensity of cosmic ray protons plotted against the intensity of cosmic ray protons in the energy range, 0.1-5.8 GeV, (from Bazilevskaya et al.¹⁹).

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✓ 5

OF EACH RUN AS A 'CARRIER' TO AVOID ADSORPTION OF THE
 ^{37}Ar ON THE WALLS OF THE TANK.

WITH A 50-DAY COLLECTION CYCLE THE EXPERIMENT
CAN'T SEARCH FOR DAY/NIGHT EFFECT, BUT ANTI-CORRELATIONS
WITH THE SUNSPOT CYCLE ARE MARGINALLY OBSERVED. (DAVIS, 1984)
THE PHYSICAL SIGNIFICANCE OF SUCH A CORRELATION (IF REAL)
IS UNCLEAR.

THE SOLAR MODEL HAS BEEN RELATIVELY STABLE FOR THE
LAST 20 YEARS, AFTER SOME INITIAL FLUCTUATIONS. THIS MODEL
COMBINES EFFECTS OF MANY PARAMETERS NOT DIRECTLY MEASURABLE
(P. 6). FOR EXAMPLE, THE RATE OF PRODUCTION OF ^{8}Rb
VARIES AS T^{17} , WHERE T IS THE TEMPERATURE AT THE
CENTER OF THE SUN. A 6% REDUCTION IN THE MODEL
ESTIMATE OF T WOULD REMOVE THE DISCREPANCY WITH EXPERIMENT.

Fig 57

Ref 54

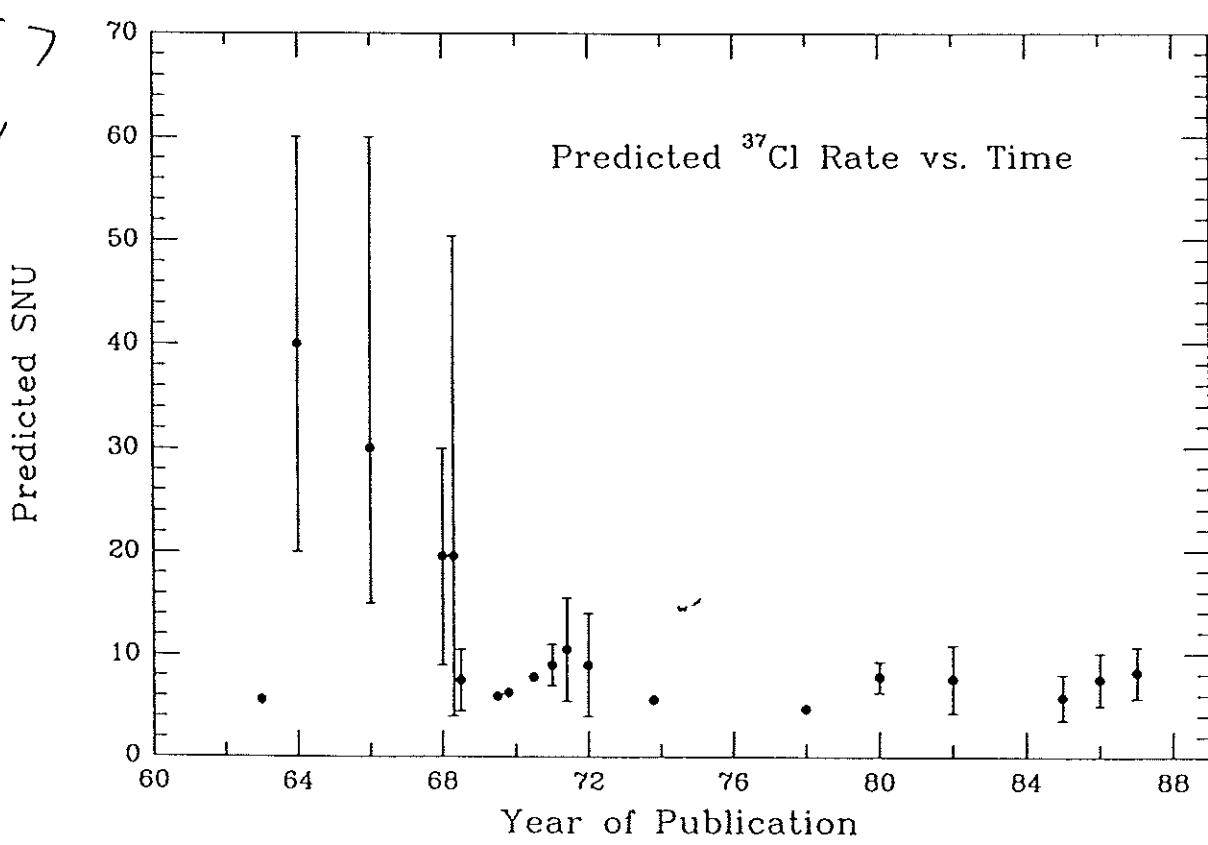


TABLE 5 ref 57

Prefatory table of some important solar parameters.

Parameter	Value
Luminosity	3.86×10^{33} erg sec $^{-1}$
Mass (M_\odot)	1.99×10^{33} g
Radius (R_\odot)	6.96×10^{10} cm
Moment of Inertia	7.00×10^{33} g cm 2
Depth of convective zone	$0.27 R_\odot (0.02 M_\odot)$
Age	$\geq 4.55 \times 10^9$ yr
Central density	156 g cm $^{-3}$
Central temperature	15.5×10^6 K
Central hydrogen abundance by mass	0.355
Effective (surface) temperature	5.78×10^3 K
Primordial helium abundance by mass	0.25 ± 0.01
Primordial ratio of heavy elements to hydrogen mass	0.0228
Neutrino flux from $p-p$ reaction	6.1×10^{10} cm $^{-2}$ sec $^{-1}$
Neutrino flux from 8B decay	5.6×10^6 cm $^{-2}$ sec $^{-1}$
Fraction of energy from $p-p$ chain	0.985
Fraction of energy from CNO cycle	0.015

FIG 58 ref 53

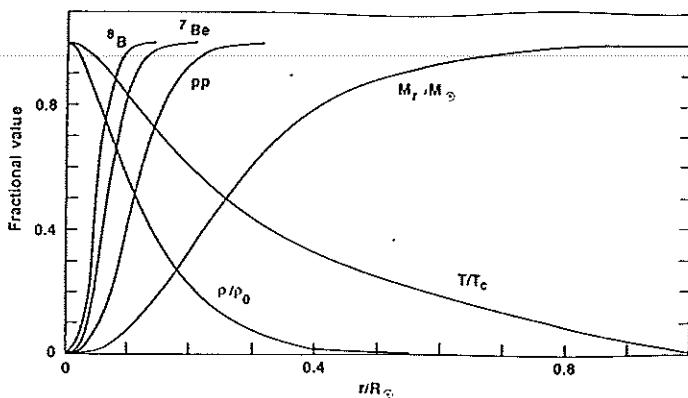


Fig. 1. Some of the important solar variables and neutrino fluxes plotted as a function of the fractional distance r/R_\odot from the center, where R_\odot is the radius of the sun. The temperature T and density ρ are given relative to their central values. $T_c = 15.5 \times 10^6$ K and $\rho_0 = 156$ g/cm 3 , respectively. The fraction of the pp, ^7Be , and ^8B neutrino fluxes produced and of the mass residing inside the indicated radial dimension are shown on the same plot. Here M_r is the mass within radius r and M_\odot is the solar mass. All the values have been calculated on the standard model and are taken from table 7 of (12).

(12). ref 59

IT IS POSSIBLE THAT 8B PRODUCTION IS SUPPRESSED IN THE SUN, AND THE HOMESTAKE SIGNAL IS ENTIRELY DUE TO NEUTRINOS FROM THE ^7Be ELECTRON-CAPTURE REACTION AT THE LEVEL OF THE STANDARD MODEL.

THE EXCITEMENT IS THAT THE PROBLEM MIGHT BE EVIDENCE FOR NEW NEUTRINO PHYSICS.

B. THE KAMIOKANDE WATER CERENKOV EXPERIMENT.

THIS UNDERGROUND EXPERIMENT, BASKING IN THE GLOW OF SN1987A, HAS PRELIMINARY EVIDENCE THAT THE SOLAR NEUTRINO RATE FROM 8B IS LESS THAN HALF THE STANDARD SOLAR MODEL PREDICTION (90% CONFIDENCE). ref 60

Fig 59 ref 61

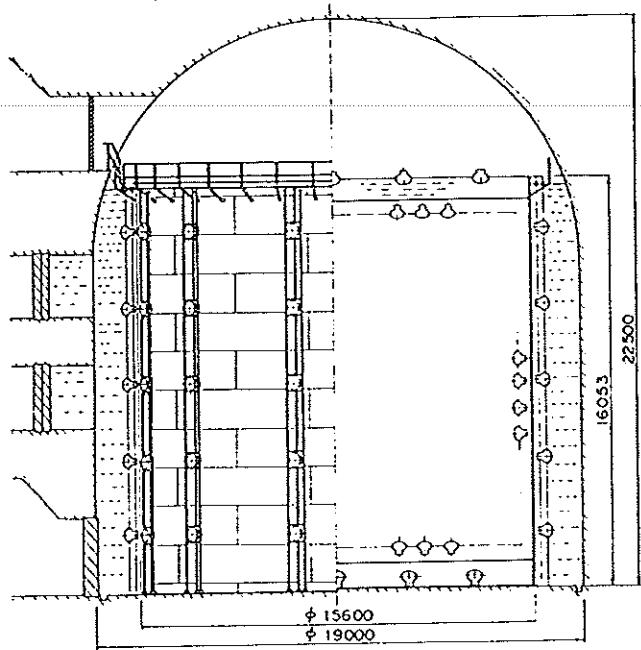
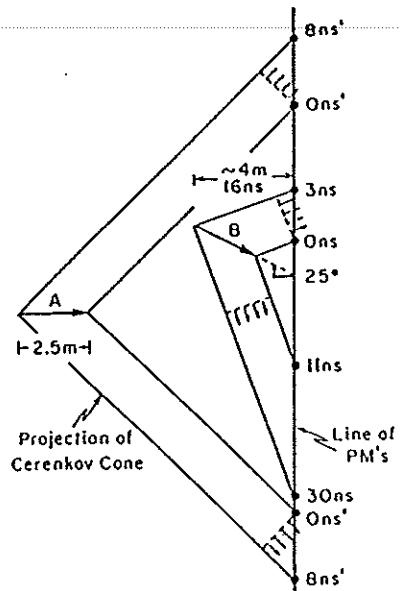


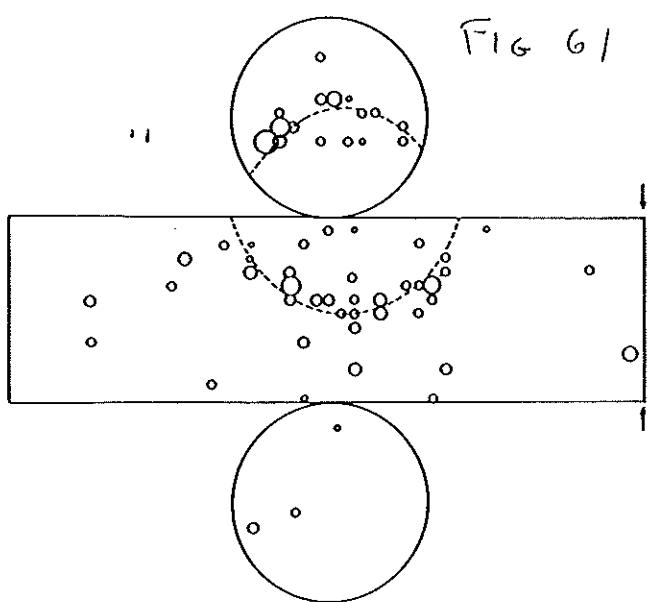
FIG. 1. Schematic view of the Kamiokande II detector. The inner detector contains 3000 tons of water of which 2140 tons are fiducial volume. It is viewed by 948 20-in.-diameter PMT's mounted on a 1-m grid on the inner surface. The outer (veto) counter surrounds the inner detector and is viewed by 123 PMT's. Dimensions in the figure are in millimeters.

Fig 60 ref 62



Timing differences across Cherenkov rings for tracks at two different angles relative to a plane of PMTs in the IMB detector.

Fig 61

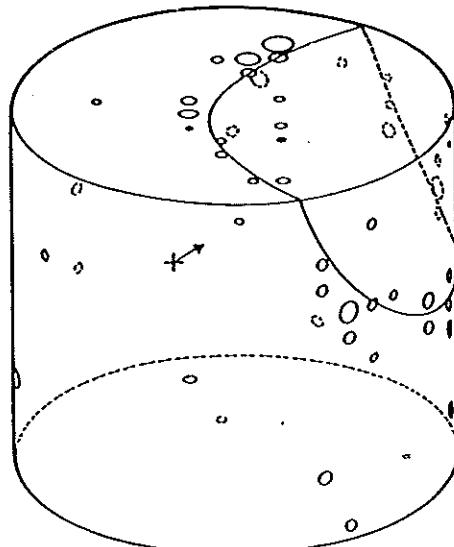


A TYPICAL SUPERNOVA NEUTRINO
INTERACTION

ref 63
KAMIOKANDE 2-P

NUM	9
RUN	1892
EVENT	139372
TIME	2/23/87 16:35:37 JST

TOTAL ENERGY 19.8 MeV



IN THE DETECTOR 1000 GIANT PHOTO MULTIPLIER TUBES LOOK INWARD ON 2000 TONS OF VERY PURE WATER. A CHARGED PARTICLE WITH $v > c/n = 0.75c$ INSIDE THE TANK EMITS CERENKOV LIGHT INTO A CONE. IF THE TRACK LENGTH IS SHORT THE CONE INTERSECTS THE WALL OF PHOTOMULTIPLIERS IN A CIRCLE. A 10-MEV ELECTRON YIELDS ~ 25 STRUCK PHOTOMULTIPLIERS. THE TIME RESOLUTION OF EACH P.M. IS $\sim 1\text{ ns}$, AND THE ENTIRE DETECTOR CAN BE READ OUT IN A FEW MS.

BACKGROUND S FROM COSMIC-RAY MUONS, AND FROM RADIOPACTIVITY IN THE WATER & WALLS LIMIT THE MINIMUM ENERGY DETECTABLE TO ABOUT 8 MEV AT PRESENT.

KAMIOKANDE WAS DESIGNED TO DETECT PROTON DECAY, WITH A TYPICAL ELECTRON SIGNAL OF 100-200 MEV. IT IS A SUBSTANTIAL ACHIEVEMENT TO HAVE LOWERED THE DETECTION THRESHOLD TO A FEW MEV.

THE NEUTRINOS ARE DETECTED VIA THE ELECTRON FROM THE REACTION $\nu_e + e^- \rightarrow \nu_e + e^-$, FIG 62 AND 63¹⁴

IN WHICH THE RECOIL ELECTRON TAKES ON THE DIRECTION OF THE NEUTRINO. BY PLOTTING EVENTS AS A FUNCTION OF ANGLE TO THE SUN A LIMIT ON THE SOLAR NEUTRINO SIGNAL IS OBTAINED (P. 9).

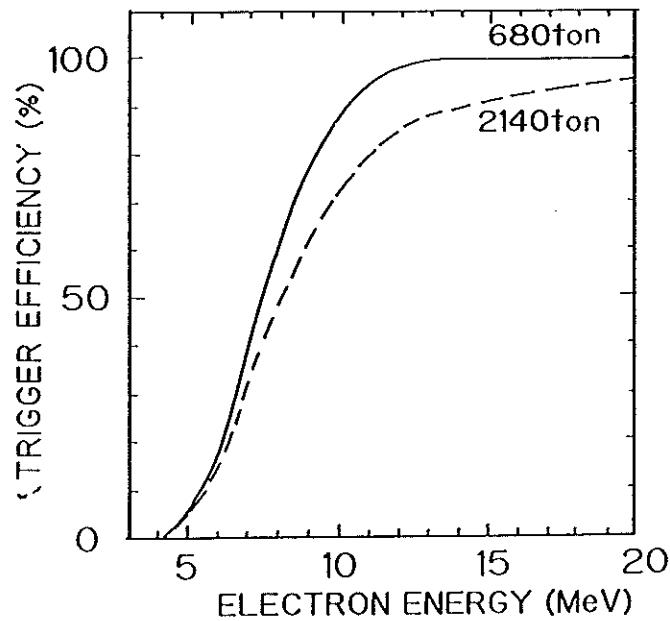


Fig. 16 Trigger efficiency of KAMIOKANDE

NO CLEAR SIGNAL OF
 SOLAR NEUTRINOS HAS
 BEEN SEEN YET IN
 KAMIOKANDE, BUT
 THIS IS STILL CONSISTENT
 WITH DAVIS' RESULT.

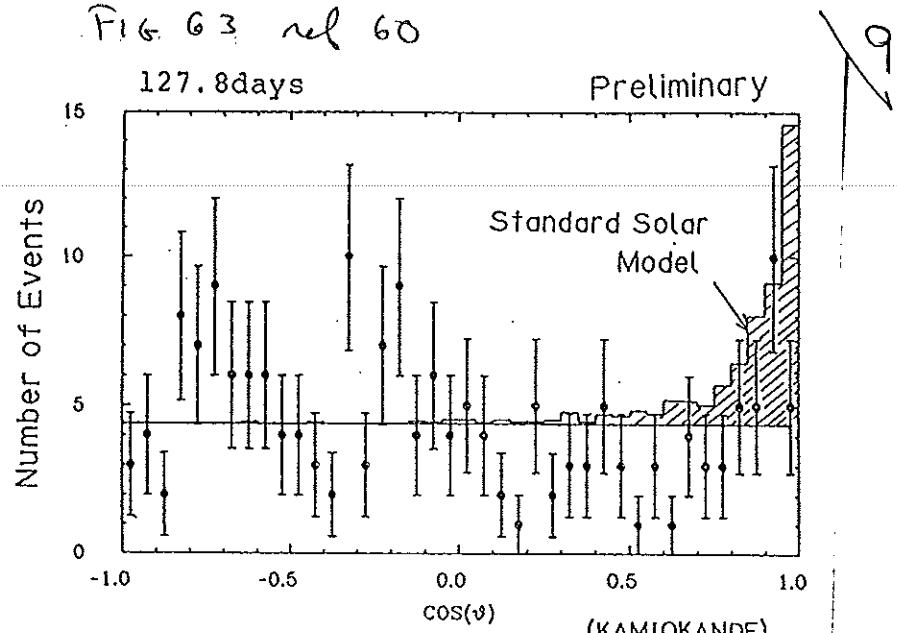


Fig.17 Directional correlation to the sun ($> 10.5 \text{ MeV}$)

C. FUTURE APPROACHES

PROPOSALS HAVE BEEN MADE FOR STUDY OF SOLAR NEUTRINOS
 WITH 7 OTHER TARGETS BESIDES ^{37}Cl AND ELECTRONS. THE
 TABLE (BANKAI & ULRICH, 1987) SHOWS THAT OF THESE ON THE
 ^{71}Ga AND THE ^{115}In EXPERIMENTS WOULD BE SENSITIVE TO
 THE PP REACTION WHICH PRODUCES 90% OF ALL SOLAR NEUTRINOS.
 HENCE THESE EXPERIMENTS CONFRONT THE SOLAR MODEL MOST DIRECTLY.

Table 6

TABLE XVII. Capture Rates Predicted by the Standard Solar Model. The capture rates predicted by the standard solar model, row 6 of Table XI (CNO corr), are given for each target (first column) and for each neutrino source (columns two through nine). The total rate is given in the last column. All event rates are in SNU.

Target	p-p	pep	hep	^7Be	^8B	^{13}N	^{15}O	^{17}F	Total
^2H	0.0	0.0	0.02	0.0	6.0	0.0	0.0	0.0	6.0
^7Li	0.0	9.2	0.06	4.5	22.5	2.6	12.8	0.1	51.8
^{37}Cl	0.0	0.2	0.03	1.1	6.1	0.1	0.3	0.003	7.9
^{40}Ar	0.0	0.0	0.02	0.0	1.7	0.0	0.0	0.0	1.7
^{71}Ga	70.8	3.0	0.06	34.3	14.0	3.8	6.1	0.06	132
^{81}Br	0.0	1.1	0.07	8.6	15.3	0.9	1.9	0.02	27.8
^{98}Mo	0.0	0.0	0.08	0.0	17.3	0.0	0.0	0.0	17.4
^{115}In	468	8.1	0.05	116	14.4	13.6	18.5	0.2	639

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THE OTHER EXPERIMENTS ARE SENSITIVE ONLY TO HIGH-ENERGY NEUTRINOS, PRIMARILY FROM 8B DECAY. THE NEW OPPORTUNITY HERE IS SENSITIVITY TO NEUTRAL-CURRENT REACTIONS SUCH AS



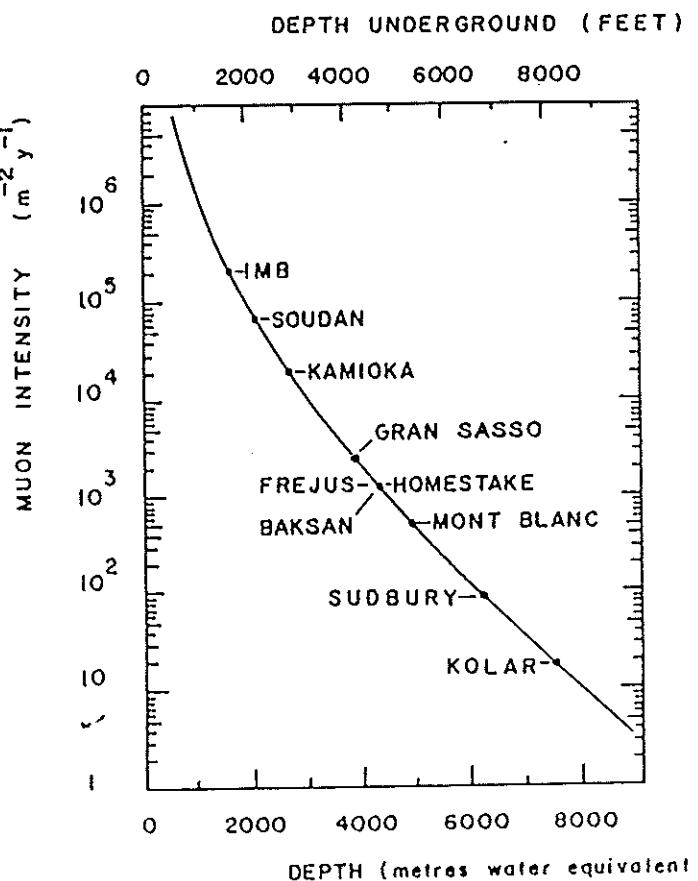
WHICH MIGHT BE RELEVANT IF THE ν_e FLUX HAS OSCILLATED TO A γ_μ (OR γ_τ) COMPONENT.

THE ISSUE OF NEUTRINO OSCILLATIONS IS COMPLICATED BY THE VIEW OF MIKHEEV, SMIRNOV & WOLFENSTEIN (MSW) THAT NEUTRINO INTERACTIONS INSIDE THE SUN CAN INCREASE THE SIZE OF THE OSCILLATION EVEN IF IT WOULD BE SMALL IN FREE SPACE. THIS FREES THE ASTRO THEORIST FROM CONSTRAINTS ON NEUTRINO OSCILLATIONS IN REACTOR AND ACCELERATOR EXPERIMENTS.

FIG 64 ref 68

AN OVERVIEW OF THE FUTURE EXPERIMENTS IS GIVEN BY FRIEDLANDER & WESNER,⁶⁷ SCIENCE 235, 755, 760 (1987).

WE BEGIN BY NOTING THE DEPTHS OF THE VARIOUS UNDERGROUND LABORATORIES ACTIVE OR PROPOSED.



D. THE ^{71}GA EXPERIMENTS

THIS IS A RADIO CHEMICAL EXPERIMENT, SIMILAR IN PRINCIPLE TO THE ^{37}Cl EXPERIMENT. HENCE THE READOUT TIME SCALE IS DAYS TO WEEKS.

THE REACTION IS $\gamma_e + ^{71}\text{GA} \rightarrow ^{71}\text{Ge} + e^-$ THRESHOLD = 0.23 MeV

THE ^{71}Ge DECAYS VIA ELECTRON CAPTURE BACK TO ^{71}GA , WITH AN 11-DAY HALF LIFE. THE K-CAPTURE X-RAY HAS 10.4 KeV.

TWO EXPERIMENTS ARE UNDER CONSTRUCTION, BAKSAN AND GALLEX, WHICH DIFFER IN THE Ge EXTRACTION PROCESS.

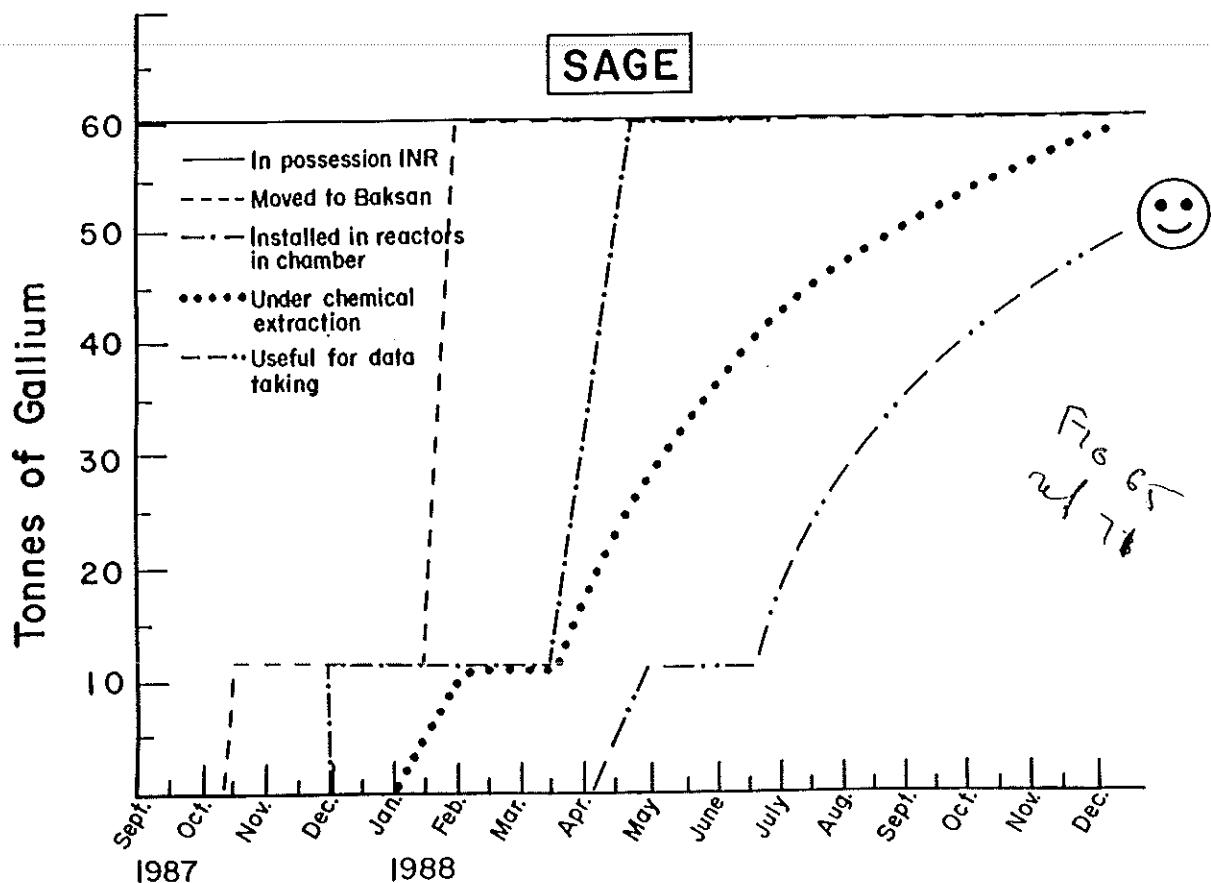
GALLEX USES Ga Cl_3 IN HCl SOLUTION AS THE TARGET. THE Ge ATOMS FORM Ge Cl_4 WHICH CAN BE BUBBLED OUT WITH He GAS, EVENTUALLY CONVERTED TO Ge H_4 AND FED INTO THE GAS OF A PROPORTIONAL COUNTER TO DETECT THE ^{71}Ge DECAY (HAMPEL, 1984).⁶⁹

THE BAKSAN EXPERIMENT USES LIQUID GALLIUM AS THE TARGET (MELTING POINT = 30°C). THE ^{71}Ge IS EXTRACTED VIA A DILUTE SOLUTION OF HCl AND H_2O_2 . AGAIN THE Ge Cl_4 IS CONVERTED TO Ge H_4 GAS AND OBSERVED IN A PROPORTIONAL COUNTER. [BARABANOV, 1984]⁷⁰

THE BAKSAN EXPERIMENT IS LOCATED IN THE CAUCASUS,⁷² AND SHOULD EVENTUALLY INCORPORATE 80 TONS OF GA. THIS WOULD IMPLY ~ 15 Ge ATOMS/DAY IN THE STANDARD SOLAR MODEL. DATA TAKING SHOULD BEGIN IN 1-2 MONTHS (APR-MAY, 1988).

Schedule of Gallium Solar Neutrino Experiment Agreed to Sept. 1987

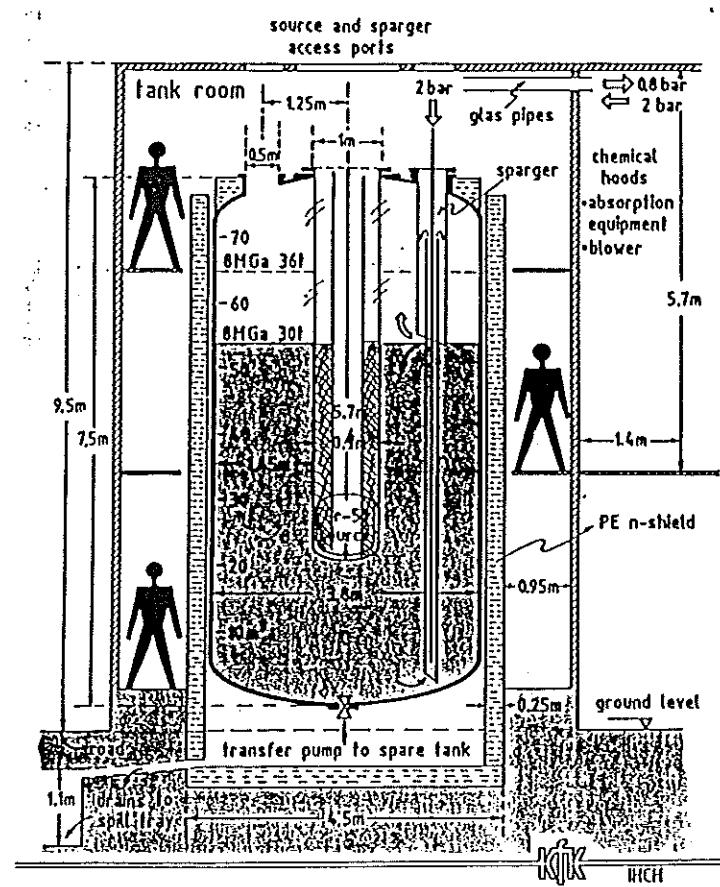
12



THE GALLEX EXPERIMENT

WILL BE LOCATED IN THE GRAN SASSO
UNDERGROUND LABORATORY NEAR
ROME. IT WILL CONTAIN 30 TONS
OF GA, AND COULD TAKE DATA
IN 1990.

Fig 66
2d 7th 4



GALLEX TARGET TANK

E. SUPER-KAMIOKANDE

A $\times 10$ version of the highly successful KAMIOKANDE II experiment is being proposed. In addition to ~ 25 times greater fiducial volume, and hence counting rate, it is hoped that the minimum energy threshold can be lowered to 5 MeV. The is dependent on further reduction of radioactivity in the water and walls. If achieved, the count rate would be ~ 50 events / day (in the standard solar model).

Table 1. Comparison of parameters between KAMIOKANDE I and SUPER-KAMIOKANDE.

TABLE 8
2464

Parameters	KAMIOKANDE I	SUPERKAMIOKANDE
Tank	16m x 16m ²	40m x 38m ²
Total mass	3000t	32000t
Fiducial mass	880t	22000t
Number of PMTs	1000	11000
% photosensitive coverage	20%	40%
Photoelectron yield/HeV	3.8	5.8
Resolution for EM shower	$0.04/\sqrt{E}$ (E in GeV)	$0.03/\sqrt{E}$ (E in GeV)
Anti-counter layer	depth > 1m	depth > 2m
PMT time resolution at 1 photoelectron	5.7ns	3ns
$\mu^+ - e^+$ decay detection eff.	70%	>95%
Accuracy in vertex determination (a)	1.5m	30cm
H/S separation (b)	yes only for non-overlapping rings	yes up to ~80% overlapping rings (c)
s/p separation	no	partly yes for $p \leq 400$ MeV/c
e/ γ separation	no	partly yes (c)

(a) for 100 MeV/c electrons

(b) $H-\pi$ or μ , $S-\gamma$, e or π .

(c) under detailed study

F. SUDBURY NEUTRINO OBSERVATORY

(-175)
THIS EXPERIMENT IS AN INTERESTING VARIATION ON THE WATER CERENKOV TECHNIQUE.

The active volume is 1000 tons of D_2O (heavy water) immersed in a larger tank of H_2O for shielding.

As for Super-Kamioonde, only neutrinos of energy $\gtrsim 5$ MeV will be detectable, due to background radioactivity.

Table 9

ref 75

Table 2
Properties of the SNO detector

Depth underground	2073 m
Cosmic ray rate	100 d ⁻¹
Cavity dimensions	20 m diameter 32 m high
D ₂ O mass	1000 tonnes
H ₂ O mass	5200 tonnes
Energy resolution (7 MeV)	16%
Angular resolution (7 MeV)	30°
Time resolution (per PMT)	7.7 ns
Spatial resolution	0.7 m

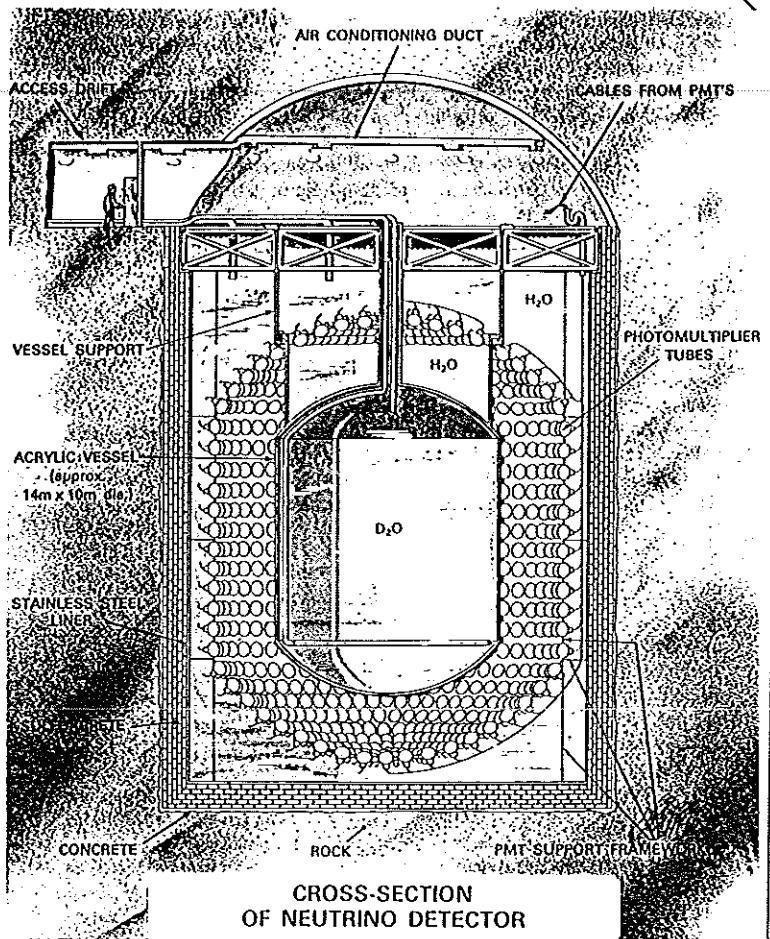
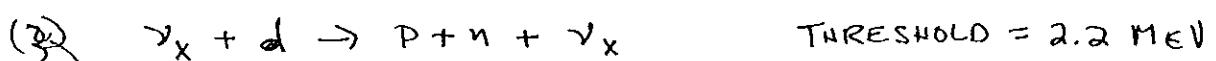
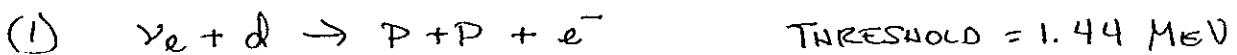


Figure 1.1: Design of the Proposed Detector.
The diameter of the cylindrical rock cavity is 20 metres.

THREE DIFFERENT NEUTRINO REACTIONS COULD BE DETECTED:



THE DEUTERIUM BREAK UP REACTION (1) HAS A LARGER CROSS SECTION THAN SCATTERING OFF ELECTRONS FOR $E_\nu > 5$ MeV, YIELDING ~ 30 EVENTS / DAY IN THE STANDARD SOLAR MODEL. THIS IS ABOUT 10 TIMES THE RATE FOR REACTION (3).

REACTION (2) [= ES] CAN BE DISTINGUISHED STATISTICALLY FROM REACTION (1) [= CC] BY THE STRONG CORRELATION OF THE ELECTRONS' DIRECTION TO THE SUN IN (2).

IN THE 3-BODY FINAL

STATE OF (1), THE

ELECTRON IS NEARLY (THO
NOT QUITE) ISOTROPIC.

REGARDING NEUTRINO

OSCILLATIONS, NOTE THAT

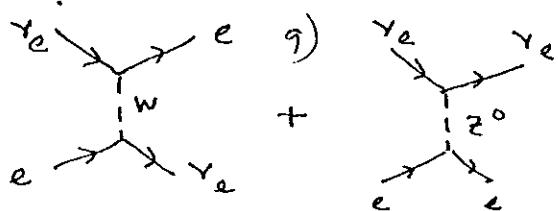
REACTION (3) IS 6 TIMES

LARGER WHEN INITIATED

BY γ_e THAN FOR γ_μ OR γ_τ .

THIS ARISES BECAUSE THERE

ARE 2 DIAGRAMS FOR γ_e :



BUT ONLY 1 FOR γ_μ OR γ_τ :

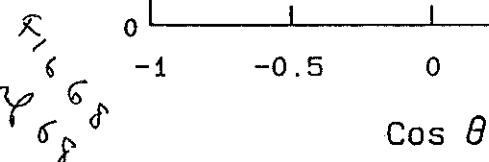
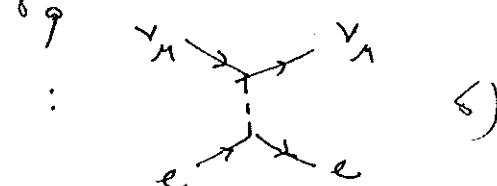


Figure 3.20: Monte Carlo prediction of the angular distribution of events after one year of data taking, with a detector with 40% photocathode coverage. A 8B ν -flux of $2 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ is assumed.



FOR EXAMPLE, IF $2/3$ OF THE γ_e HAVE OSCILLATED TO γ_μ THEN

THE OBSERVATION SHOULD BE

$$\frac{\text{RATE}(1)}{\text{RATE}(3)} = \frac{\gamma_3}{\gamma_3(\frac{1}{10}) + \gamma_3(\frac{1}{6})(\frac{1}{10})} = 7.5$$

INSTEAD OF 10 IF NO OSCILLATIONS OCCURRED.

REACTION (2), $\nu + d \rightarrow p + n + \bar{\nu}$, IS INDEPENDENT OF NEUTRINO TYPE, AND WOULD SERVE AS A SEPARATE MONITOR OF THE TOTAL NEUTRINO FLUX. BUT THERE IS NO CHERENKOV SIGNAL!

IF THE NEUTRON IS CAPTURED BY ANOTHER NUCLEUS BEFORE LEAVING THE TANK A SEVERAL-MeV γ RAY IS EMITTED, WHICH MIGHT BE DETECTED BY A RECOIL ELECTRON FROM AN EVENTUAL COMPTON SCATTER. THE NEUTRON-CAPTURE CROSS SECTION ON DEUTERIUM IS SMALL, SO 0.25% NaCl COULD BE ADDED TO INCREASE THE CAPTURE RATE BY 4. PROBLEMS REMAIN: THE ENERGY OF THE COMPTON ELECTRONS IS LOW, AND THEIR ANGULAR DISTRIBUTION IS SIMILAR TO THAT FOR REACTION (1)

TIME SCALE: 4 YEARS AFTER APPROVAL TO DATA TAKING.

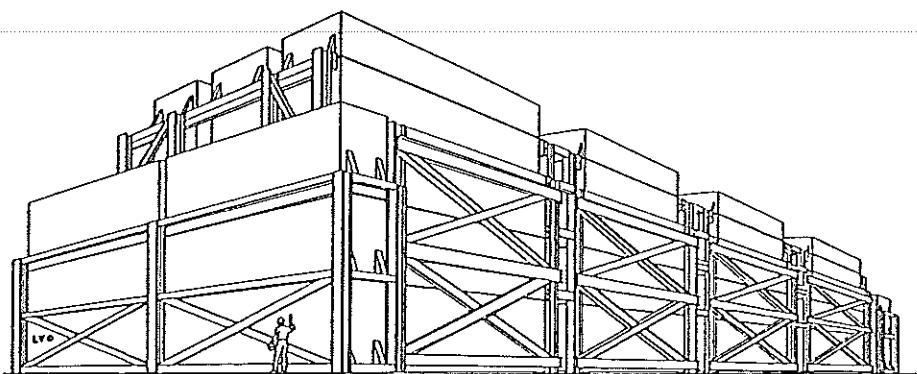
G. LARGE VOLUME DETECTOR (LVD) IN GRAN SASSO.

(16) THIS DEVICE IS BIG BUT CRUDG - A LARGE VERSION OF THE COSMIC-RAY DETECTORS OF THE 1930'S.

IT CONSISTS OF 1500 MODULES, EACH OF 1.5 m^3 OF LIQUID SCINTILLATOR. LAYERS OF 'STREAMER TUBES' (A CHEAP VERSION OF A PROPORTIONAL COUNTER) ARE PLACED BETWEEN THE SCINTILLATOR MODULES TO PROVIDE 1-CM POSITION RESOLUTION ON THOSE TRACKS WHICH EXIT THE MODULES. BUT ELECTRONS WITH $E_e < 100 \text{ MeV}$ WILL TYPICALLY STOP IN THE MODULE IN WHICH THEY ORIGINATE, YIELDING NO ANGULAR INFORMATION.

TIME AND ENERGY MEASUREMENTS REMAIN. THE ENERGY THRESHOLD WILL BE 15 MeV, AS FOR ALL BIG UNDERGROUND DEVICES.

LVD WILL BEGIN OPERATION IN 1988.



69 Fig. 4. The LVD detector.

TABLE 1
The main characteristics of LVD.

Area	2332 m ²
Geometrical acceptance	~ 7000 m ² sr
Length	40 m
Height	13.2 m
Width	12 m
Volume of scintillator	2280 m ³
Mass of scintillator	1800 t
Mass of steel	1800 t
Number of tracking channels	100 000
Number of streamer tubes	20 000
Number of phototubes	6 400
Analog channels	12 800
Tracking spatial resolution	4 mrad
Energy resolution	20%
Energy threshold	~ 3 MeV

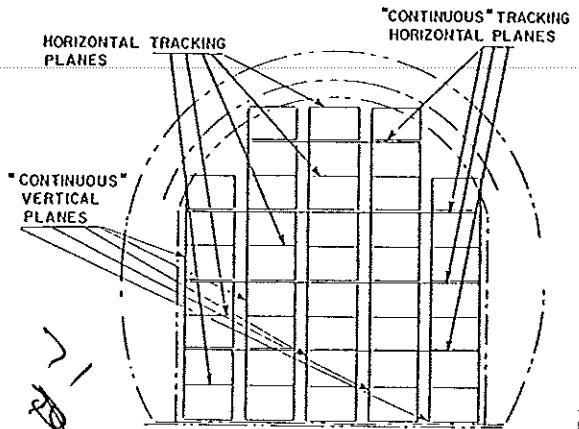


Fig. 11. Tracking planes of the LVD detector.

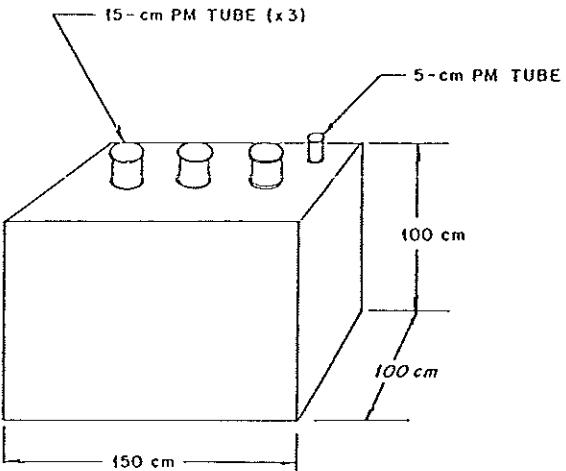


Fig. 5. The basic scintillator counter of the LVD. The LVD will have 1520 such counters.

H. ICARUS AT GRAN SASSO

THIS EXPERIMENT IS APPROVED BUT NOT DESIGNED!

A POSSIBLE CONFIGURATION IS A LARGE (5000 TON) CYLINDER OF LIQUID ARGON WHICH SERVES AS TARGET AND IONIZATION CHAMBER.

IN PURE ARGON ELECTRONS CAN DRIFT SEVERAL METERS WITHOUT BEING ATTACHED. THE DETECTOR IS SUBDIVIDED INTO GIANT CAPACITORS WITH ~ 2 M GAP, AND A GRID READOUT AT EACH ANODE PLANE - (P. 18). THE GRIDS ARE LARGELY TRANSPARENT, PERMITTING 3 READOUTS OF DIFFERENT SPATIAL ORIENTATION. THE SIGNAL IS INDUCED

ICARUS TUBE

Table 8. Main Parameter List

Parameter	Value
Active Volume	4600 m ³
Diameter	14.0 m
Length	30.0 m
Number of Planes	3 x 2
Drift Length	2.30 m
Stereo Angle	10 degrees
Drift field	1.0 kV/cm
High Voltage	230 kV
Max. Drift Time	1.2 msec
Number of Channels	100,000
Spatial Resolution	2.0 mm
Magnetic Field	2.0 Tesla
Total Memory	200 Mbytes

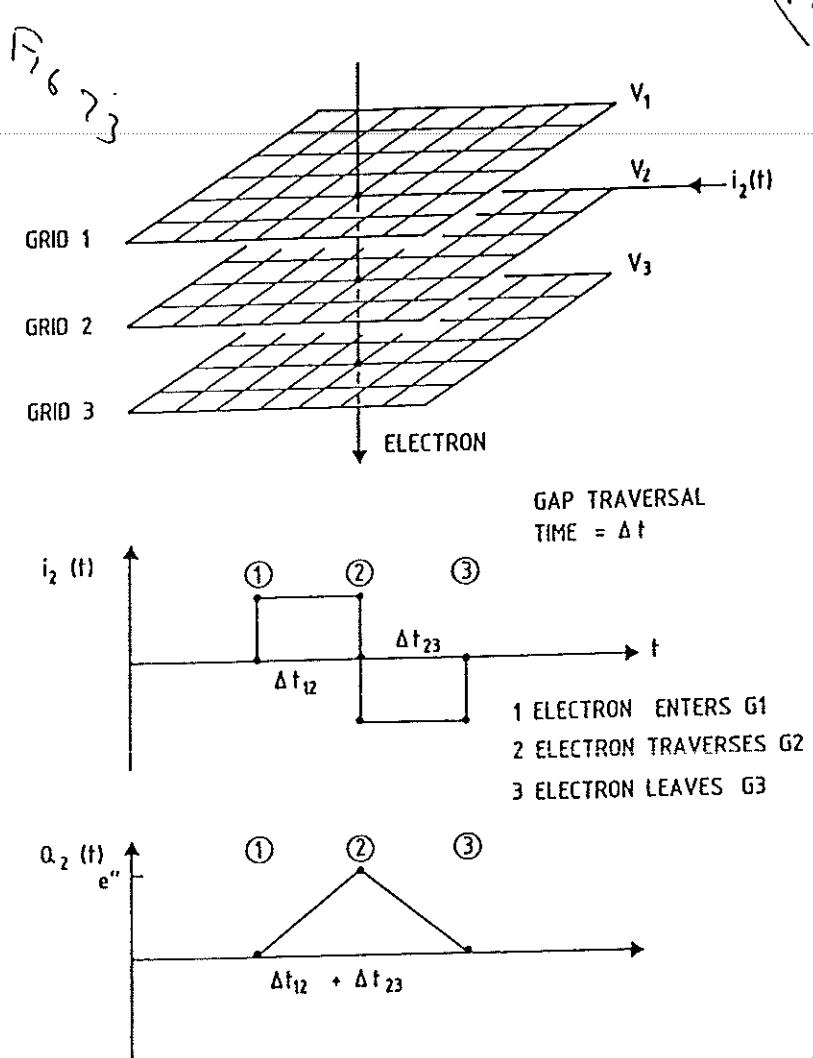


Figure 39. Principle diagram of pulse formation by imaging the drifting electrons on a transparent grid (non-destructive read-out).

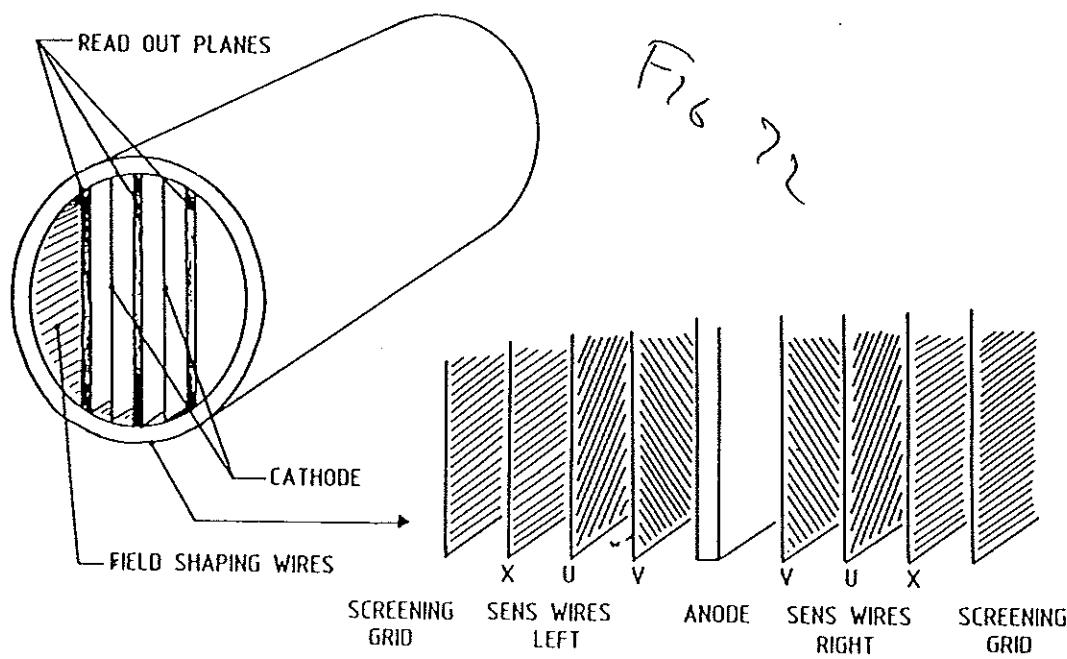


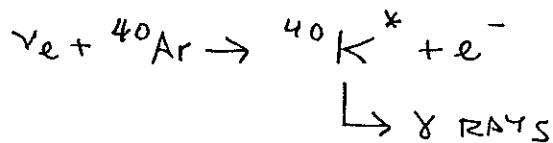
Figure 43. Layout of read-out planes and cathodes in the detector dewar.

ON THE GRID SENSE WIRES AS THE ELECTRONS DRIFT BY.

2-MM SPATIAL RESOLUTION SHOULD BE ACHIEVABLE.

IN ADDITION, THE INDUCED CHARGE IS DIGITIZED IN SMALL TIME BINS, WHICH PERMITS RECONSTRUCTION OF THE TRACKS ALONG THE AXIS \perp TO THE ANODE (TIME PROJECTION CHAMBER).

BESIDES DETECTING ELECTRONS FROM $\nu + e \rightarrow \nu + e$
 THERE IS AN INTERESTING ABSORPTION REACTION FOR ^{40}Ar
 POINTED OUT BY RAGHAVAN (1986) ?
 $\frac{\pi}{J_T} (\text{MeV})$ (inset)



THE REACTION THRESHOLD IS 5.9 MeV,

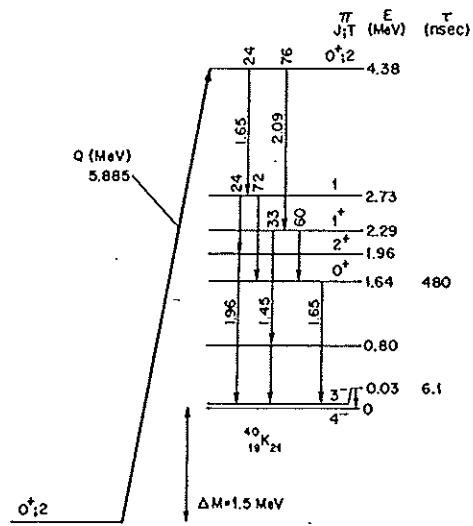
SO ONLY ${}^8\text{B}$ -NEUTRINOS COULD BE

STUDIES. IF THE 2-MEV γ RAYS

CAN BE DETECTED ALONG WITH THE

ELECTRON THE SIGNAL WILL BE $\frac{F_1}{2} \frac{F_6}{7} \frac{7}{4}$
 $\frac{F_2}{8} \frac{7}{8}$ FIG
VERY CLEAR.

FIG. 1. Level scheme of ^{40}Ar - ^{40}K relevant to ν_e capture in argon.

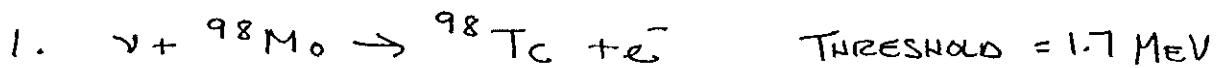


WITH A 5-MeV DETECTION THRESHOLD THE ^{40}Ar REACTION
 WOULD DOMINATE $\nu + e$, LEADING TO ~ 15 EVENTS/DAY IN THE
 STANDARD SOLAR MODEL [BAHCALL ET AL, PHYS. LETT. 178B, 324 (1986)].

A "B" TARGET WOULD ALSO HAVE NEUTRINO ABSORPTION TO AN EXCITED STATE OF ^{11}C , YIELDING X-RAYS ALONG WITH THE ELECTRON. RAGHAVAN (1987) PROPOSES A DETECTOR BASED ON BORATED LIQUID SCINTILLATOR.

I. OTHER RADIOCHEMICAL EXPERIMENTS

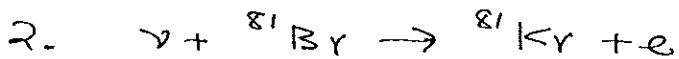
AT LEAST 4 MORE RADIOCHEMICAL EXPERIMENTS ARE UNDER DISCUSSION



THE INTEREST HERE IS THAT ${}^{98}\text{Tc}$ HAS A HALF LIFE OF $81/4 \times 10^6$ YEARS. THE TARGET IS GEOLOGICAL - MOLYBDENITE ORE,

BUT IT MUST BE FROM A LOW-RADIOACTIVITY REGION!

DUE TO ITS LONG HALF LIFE, ${}^{98}\text{Tc}$ WILL NOT USEFULLY DECAY IN ANY DETECTOR, AND MUST BE EXTRACTED IN A MASS SPECTROMETER - ON A SCALE LIKE LAWRENCE'S CALUTRONS OF THE 1940'S



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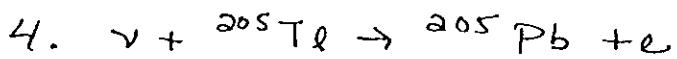
THIS COULD BE STUDIED IN THE HOMESTAKE MINE APPARATUS, REPLACING CrCl_4 WITH CHBr_3 OR $\text{C}_2\text{H}_2\text{Br}_4$.

THE REACTION THRESHOLD IS 0.5 MEV, SO THERE WOULD BE CONSIDERABLE SENSITIVITY OF NEUTRINOS FROM ${}^7\text{Be}$ DECAY.

THERE IS SOME UNCERTAINTY AS TO THE ${}^{81}\text{Br}$ γ -ABSORPTION CROSS SECTION, AS VARIOUS STATES OF ${}^{81}\text{Kr}$ ARE EXCITED ...



${}^7\text{Be}$ HAS A 53-DAY HALF LIFE, BUT ONLY 10% DECAY TO γ -RAYS.



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${}^{205}\text{Pb}$ HAS A HALF LIFE OF 1.5×10^7 YEARS, BUT Tl IS AVAILABLE ONLY FROM SHALLOW DEPOSITS \Rightarrow MUON ACTIVATION.

THE γ -ABSORPTION CROSS SECTIONS ARE UNCERTAIN AT PRESENT.

J. EXOTIC DETECTORS

DETECTOR CONCEPTS STILL IN AN EARLY STAGE OF DEVELOPMENT WILL BE DISCUSSED IN LECTURE 4.

II SUPERNOVA NEUTRINOS

THE FIRST CLEAN CONTRIBUTION OF ASTROPHYSICS TO PARTICLE PHYSICS IN 35 YEARS CAME WITH THE OBSERVATION OF NEUTRINOS FROM SN 1987A IN THE KAMIOKANDE, IMB, BAKSAN AND LSD DETECTORS.

KAMIOKANDE

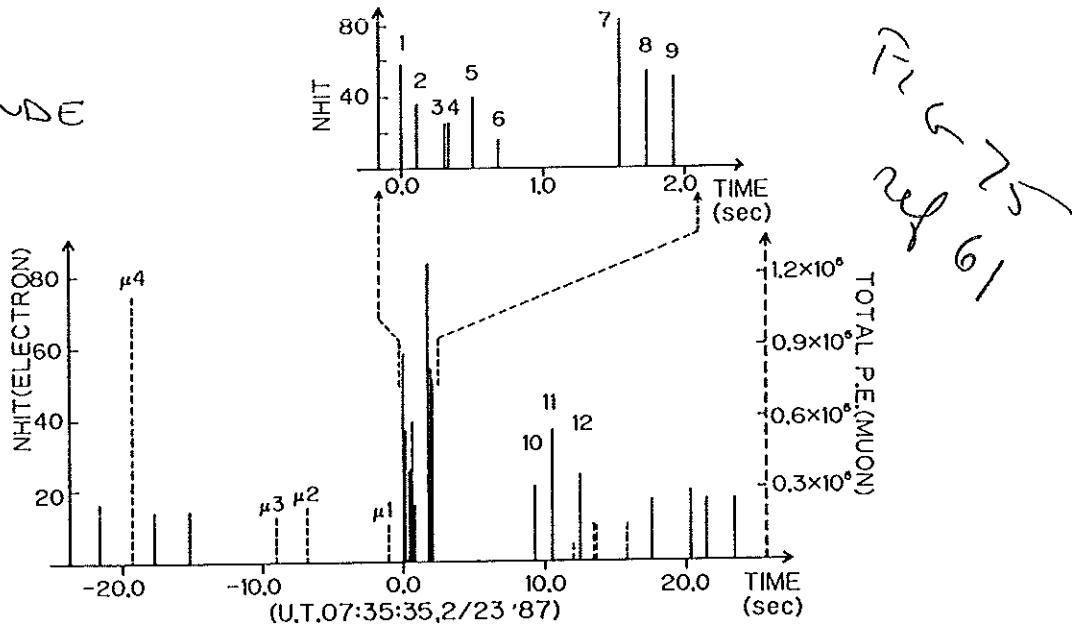


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events μ_1 - μ_4 are muon events which precede the electron burst at time zero. The upper right figure is the 0-2-sec time interval on an expanded scale.

THE ISSUE IS THE NEUTRINO MASS. THE 12 EVENTS OBSERVED BY KAMIOKANDE ARRIVED WITHIN A 12-SEC INTERVAL, AND HAVE A RANGE OF ENERGIES FROM 6 TO 36 MEV. THE DISTANCE TO SN 1987A IS $\sim 50 \text{ kpc} \sim 1.5 \times 10^{21} \text{ m}$

IF THE NEUTRINOS HAVE MASS M , THE FLIGHT TIME IS

$$t \approx \frac{d}{v} \sim \frac{d}{c} \left(1 + \frac{M^2}{2E^2}\right)$$

THE SPREAD OF TIMES AS A FUNCTION OF ENERGY LEADS TO

$$\Delta t \sim E_{\text{MIN}} \sqrt{\frac{2c\Delta t}{d}} \quad \text{IF } E_{\text{MAX}} \gg E_{\text{MIN}}$$

$$\sim 6 \text{ MeV} \sqrt{\frac{2(3 \times 10^8) \cdot 12}{1.5 \times 10^{21}}} \sim 12 \text{ eV}$$

OF COURSE THE TIME SPREAD MAY HAVE NOTHING TO DO WITH NEUTRINO MASS, SO WE READILY CONCLUDE $M_\nu \leq 20 \text{ eV}$, A LIMIT AS GOOD OR BETTER THAN ANY OBTAINED IN THE LABORATORY (FROM DETAILS OF THE ${}^3\text{H}$ β -DECAY SPECTRUM).

ASIDE FROM THE TASK OF WAITING FOR THE SUPERNOVA, DETECTING SUPERNOVA NEUTRINOS IS EASIER THAN SOLAR NEUTRINOS

- SUPERNOVA NEUTRINOS SHOULD ALL ARRIVE WITHIN A FEW-SECOND PULSE.
- THE ENERGY SPECTRUM EXTENDS TO 40 MeV WHERE THE SIGNAL IS CLEANER
- THERE IS A SIGNIFICANT COMPONENT OF $\bar{\nu}_e$, WHICH WILL BE ABSORBED IN ANY DETECTOR VIA $\bar{\nu}_e + p \rightarrow n + \bar{e}$ WITH A LARGE CROSS SECTION.

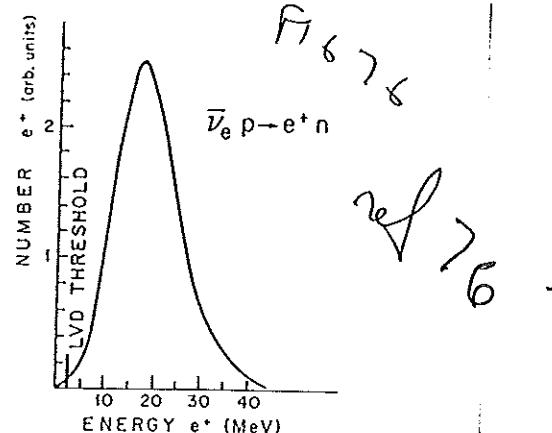


Fig. 14. Calculated energy spectrum of the positron in $\bar{\nu}_e + p \rightarrow N + e^+$. LVD threshold for detection of e^+ is 3 MeV.

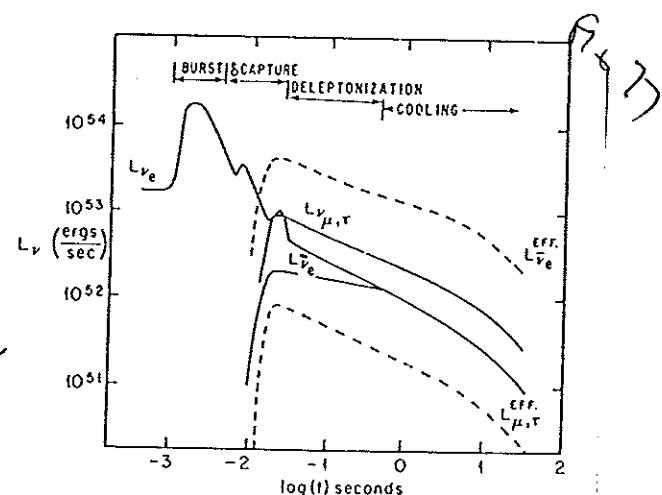


Fig. 13. Neutrino emission luminosity during various stages of stellar collapse.

THE FOUR REPORTS OF SUPERNOVA NEUTRINO EVENTS ARE

KAMIOKANDE : HIRATA ET AL, PHYS. REV. LETT. 58, 1490 (1987)

85 IMB : BIONTA ET AL, PHYS. REV. LETT. 58, 1494 (1987)

86 BAKSAN : ALEKSEEV ET AL, JETP LETT. 45, 588 (1987)

87 LSD : AGLIETTA ET AL, EUROPHYS. LETT. 3, 1315 (1987)

THE KAMIOKANDE EVENTS INCLUDE
SEVERAL WHICH ARE WELL CORRELATED
IN ANGLE TO SN1987A. THESE
WOULD LIKELY COME FROM $\nu_e l \rightarrow \nu_e l$,
AS $\bar{\nu}_e p \rightarrow n e^+$ YIELDS POSITRONS
WITH A BROAD ANGULAR DISTRIBUTION.
IN PARTICULAR, THE EARLIEST 2
EVENTS ARE THE BEST CORRELATED,
CONSISTENT WITH MODELS THAT ONLY
 ν_e 'S ARE PRESENT AT EARLY TIME
IN A SUPER NOVA (P. 22)

NOTE THAT THE ABSOLUTE TIME
OF THE KAMIOKANDE EVENTS HAS
AN UNCERTAINTY OF 1 MINUTE.

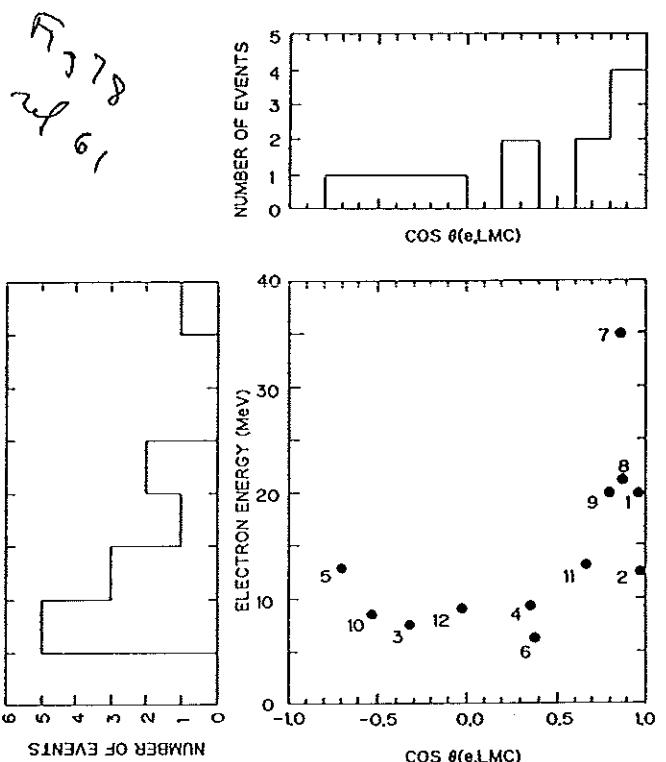
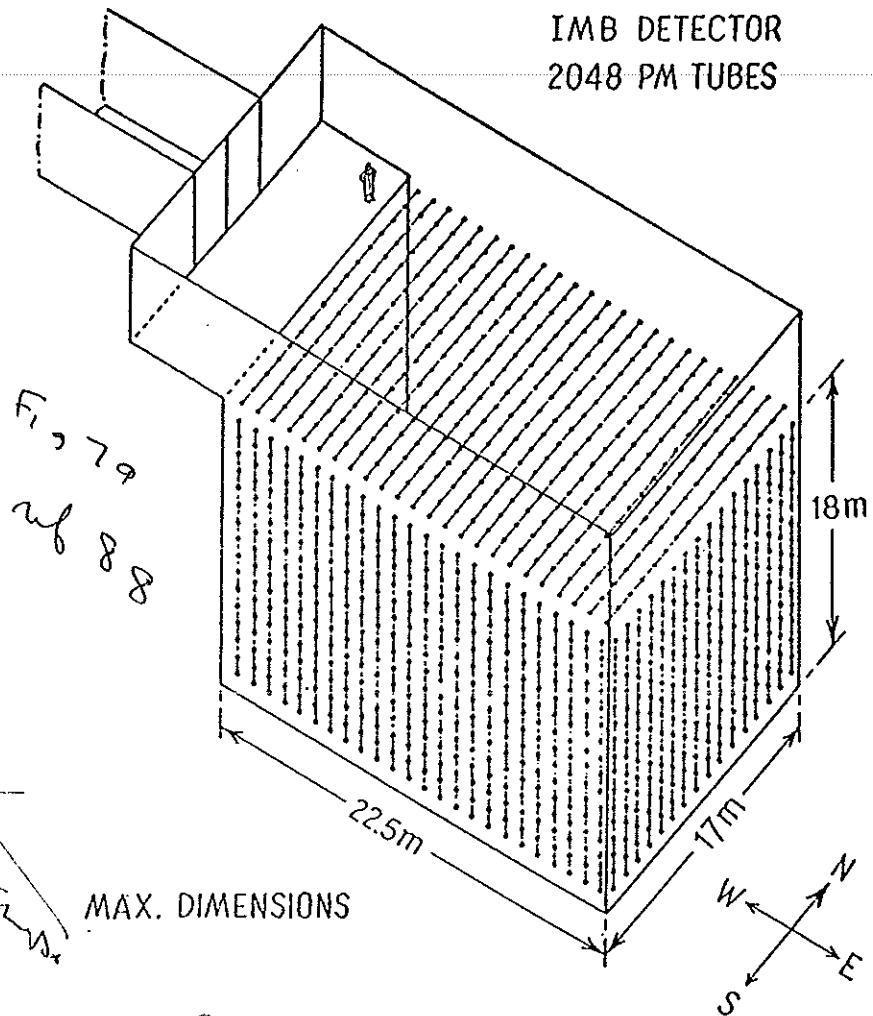


FIG. 3. Scatter plot of the detected electron energy in megaelectronvolts and the cosine of the angle between the measured electron direction and the direction of the Large Magellanic Cloud. The number to the left of each entry is the time-sequential event number from Table I. The two projections of the scatter plot are also displayed.

THE IMB DETECTOR

(IRVINE - MICHIGAN - BROOKHAVEN)
 IS A LARGE WATER CERENKOV
 DETECTOR OF 3300 TONS
 FICTIONAL VOLUME. ITS
 THRESHOLD FOR ELECTRON
 DETECTION WAS 20 MeV,
 LEADING TO A LOWER NO.
 OF EVENTS THAN KAMIOKANDE,
 DESPITE LARGER SIZE.



THE LSD DETECTOR

CONSISTS OF 90 TONS
 OF LIQUID SCINTILLATOR

(THE PRECURSOR OF LVD, P. 17)

IT HAS AN ELECTRON
 THRESHOLD OF 6 MeV,
 BUT LITTLE ANGULAR
 INFORMATION.

NOTE THAT LIQUID
 SCINTILLATOR IS
 SENSITIVE TO THE
 γ -RAYS FROM e^+
 ANNIHILATION, VIA
 COMPTON SCATTER

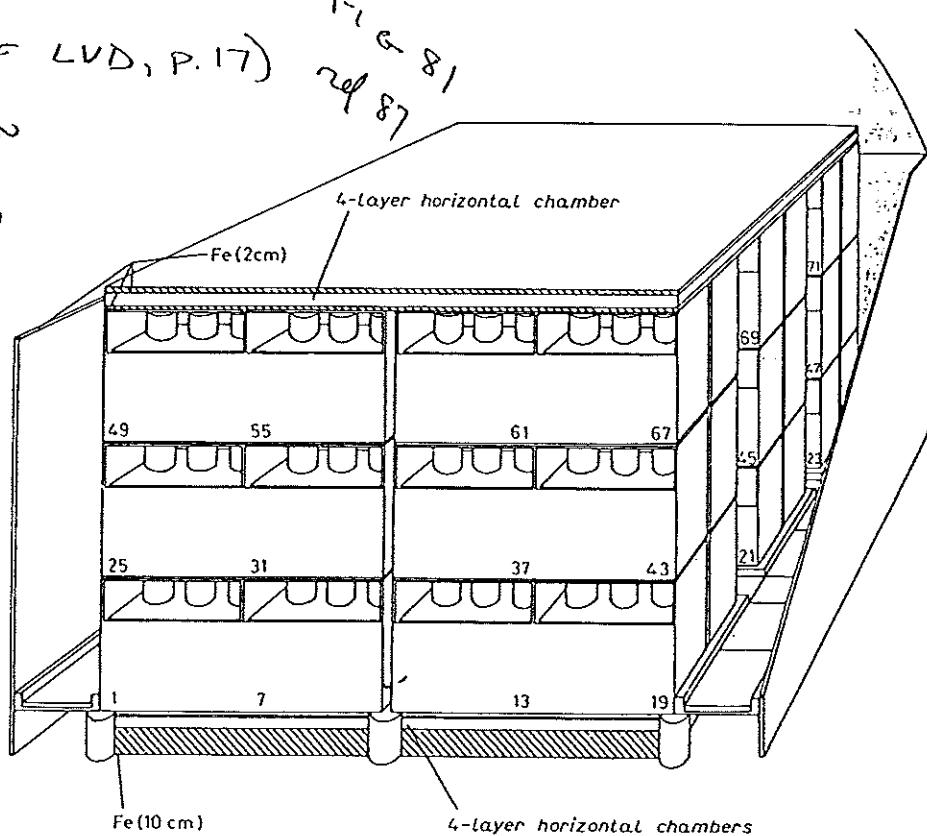


Fig. 1. – The 90 ton liquid scintillation detector (LSD) running in the Mont Blanc Underground Neutrino Observatory (UNO).

The LSD detector (fig. 81) consists of 90 tons of liquid scintillator (the precursor of the LVD detector, fig. 69). It has an electron threshold of 6 MeV, but little angular information. Note that liquid scintillator is sensitive to the γ -rays from e^+ annihilation via Compton scatter, while a water Čerenkov detector is not. Hence the liquid scintillator detectors are especially sensitive to low-energy $\bar{\nu} + p \rightarrow n + e^+$.

Fig. 81. The 90-ton liquid scintillator detector (LSD) in the Mont Blanc Underground Neutrino Observatory.⁸⁷

The controversy is that the reported events fall into 2 groups 5 hours apart!

Fig. 82. Signals detected at 2:52:36 UT on 23 Feb. 1987. a the LSD detector,⁸⁷ b the Baksan detector.⁸⁶

WHILE A WATER ČERENKOV DETECTOR IS NOT, HENCE THE LIQUID SCINTILLATOR DETECTORS ARE ESPECIALLY SENSITIVE TO LOW-ENERGY $\bar{\nu}_e + p \rightarrow n + e^+$.

THE BAKSAN DETECTOR IS ALSO BASED ON CELLS OF LIQUID SCINTILLATOR. THEIR ELECTRON THRESHOLD WAS 10 MEV, AND THE EVENT TIME WAS KNOWN TO ~ 2 SEC.

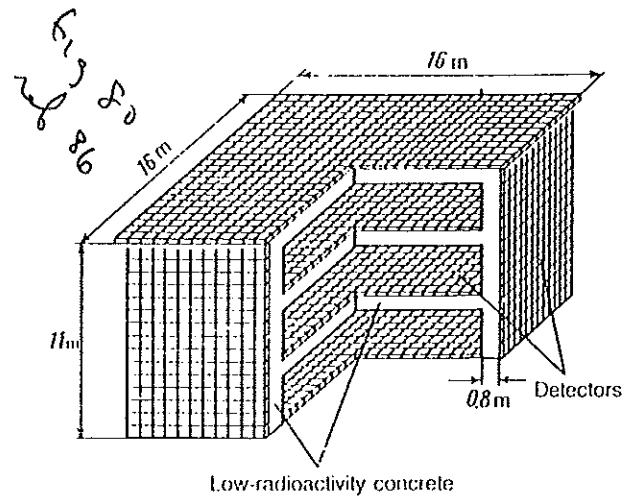


FIG. 1. The Baksan underground scintillation telescope.

THE CONTROVERSY IS THAT THE REPORTED EVENTS FALL INTO 2 GROUPS 5 HOURS APART!

FIG 82

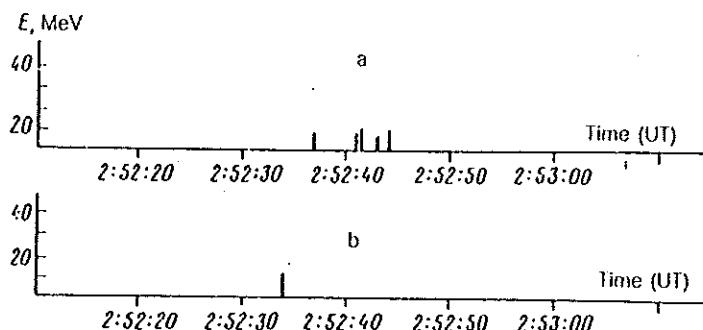


FIG. 2. Signals detected by two installations at 2:52:36 UT on 23 February 1987. a—The Soviet-Italian LSD installation; b—the Baksan telescope.

F16 83

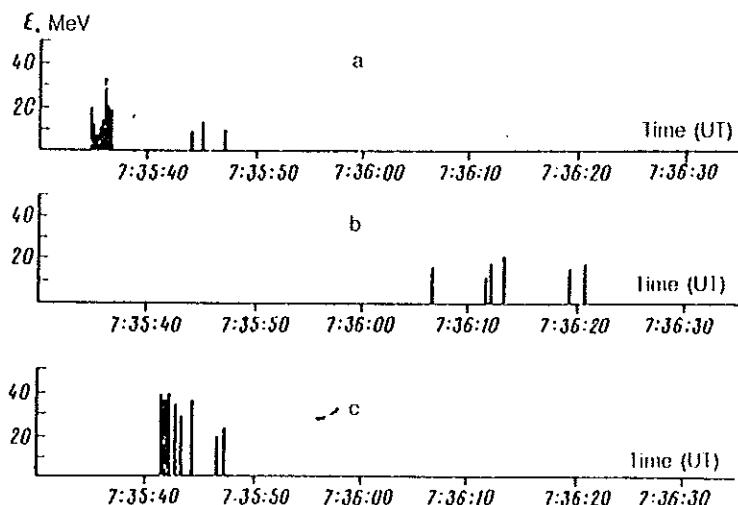


FIG. 3. Signals detected at 7:35 UT on 23 February 1987. a—at the Japanese detector; b—at the Baksan telescope; c—at the American detector.

CERTAIN 3RD-PARTY OBSERVERS PREFER TO REDEFINE THE EVENTS SLIGHTLY, LEADING TO A SCENARIO THEY PREFER.

THIS INVOLVES TWO REAL BURSTS OF NEUTRINOS, THE FIRST BEING THE 'REAL SUPERNOVA' BUT CONTAINING ONLY LOW ENERGY EVENTS, WHILE THE SECOND IS NEW ASTROPHYSICS, PERHAPS FORMATION OF A BLACK HOLE.

TABLE 12

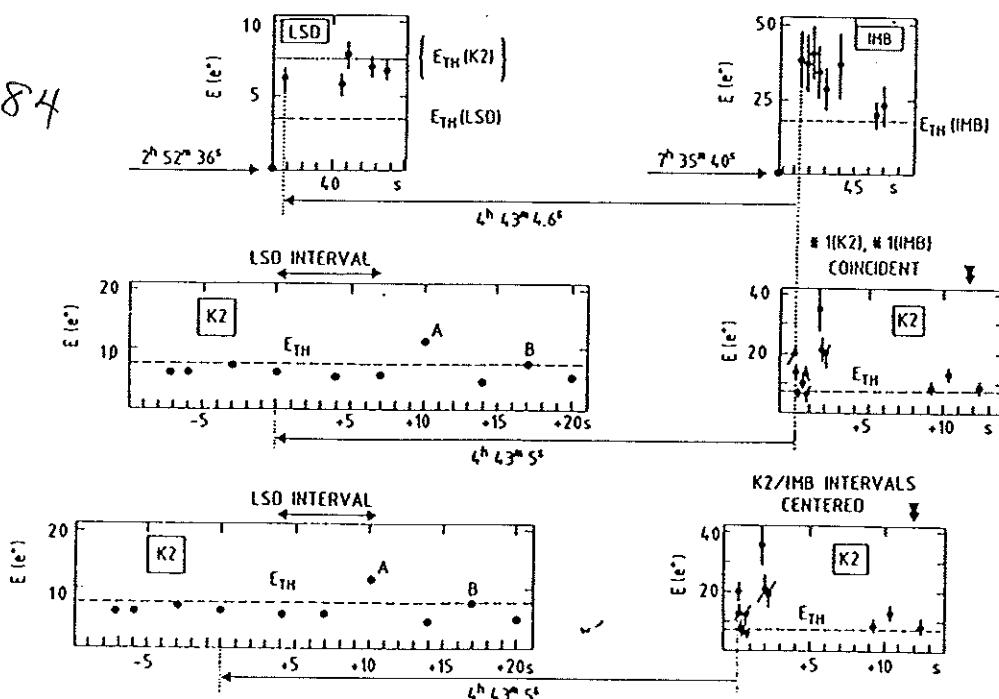
Table 2: Neutrino Data		
Time (UT) February	Detector (threshold* /size)	# of Events (E -range/Duration)
23 2h 52m	Mt. Blanc (7 MeV/90 T) ⁺	5 (6-10 MeV/7 sec)
" ± 1 min	Kamioka (8 MeV/2.14 kT)	2 (7-12 MeV/10 sec)
" "	IMB (30 MeV/5 kT)	none reported
" "	Baksan (11 MeV/130 T) ⁺	none reported
23 7h 35m (± min)	Kamioka (7 MeV/90 T)	11 (7-35 MeV/13 sec)
23 7h 35m	IMB (30 MeV/5 kT)	8 (20-40 MeV/4 sec)
" "	Baksan (11 MeV/130 T) ⁺	3 (12-17 MeV/10 sec)
" "	Mt. Blanc (7 MeV/90 T) ⁺	2 (7-9 MeV/13 sec)
sum of pulses	Homestake ν_e (0.7 MeV/615 T)**	consistent with background
		Optical
23 9h 25m	lack of sighting	$m_v \gtrsim 8$ magnitude
23 10h 40m	photograph	$m_v = 6$ magnitude
24 10h 53m	discovery	$m_v = 4.8$ magnitude

*Threshold is when efficiency drops to $\lesssim 50\%$ (sub-threshold events are therefore possible).

⁺These detectors are liquid scintillators with $H_{2n+n}C_n$, thus have ~ 1.39 more free protons than H_2O detectors of same mass.

**The Homestake detector is only sensitive to ν_e 's. It is made of C_2Cl_4 .

Fig 84



IS ASTRO PARTICLE PHYSICS AN ART OR A SCIENCE?