Present Status and Future of Kamiokande

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ABSTRACT

After a brief review of the physics results from Kamiokande-I and -II the current status of the Kamiokande-II experiment is presented with emphasis placed on search for nucleon decays and detection of solar neutrinos. The Superkamiokande project, a future plan of the Kamioka underground experiment, is also described.

1. Introduction

The Kamioka underground experiment, Kamiokande, has been known with its outstanding accomplishment, a high-sensitivity search for nucleon decays, the first detection of neutrinos emitted from a stellar-collapse event (SN1987A), and, more recently, the real-time observation of solar neutrinos. In addition, there are a number of other physics themes which can be studied in the Kamiokande experiment. Table I gives a summary of the physics results (including some expected results in near future) from the Kamiokande experiment since its startup [1- 16].

As a future plan of the Kamioka underground experiment, the Superkamiokande project has been proposed. The physics themes investigated with this experiment are essentially the same as those listed in Table I, but with great improvements in physics capabilities as discussed in section 4.

The Kamiokande detector is an imaging water-Cherenkov detector located 1,000 m underground in the Kamioka mine, about 300 km west of Tokyo. Pure water of 3,000 tons is contained in a 16 m high, 15.6-m-diameter cylindrical steel tank, 2140 tons of which is viewed by 948 twenty-inch photomultiplier tubes (PMT's) covering 20% of the tank surface. This inner detector is surrounded by a 4π water-Cherenkov anticounter layer at least 1.5 m thick, viewed by 123 twenty-inch PMT's. A more detailed description of the Kamiokande detector is given elsewhere [5,6,17]. Table I gives some selected parameters of the most recent [9] Kamiokande-II, where those of the proposed Superkamiokande are also listed. Figure 1 compares schematically the Kamiokande-II and the Superkamiokande detectors.

Actually, the Kamiokande detector has been continually improved. The first phase of the experiment (July 1983 - November 1985) is called Kamiokande-I. It was initially operated with no anticounter layer, which was constructed later in October - December 1984. The second phase, Kamiokande-II, was aimed at observing solar neutrinos, and operated since November 1985 with a new electronics system capable of recording the arrival time of each PMT signal in addition to its charge. The continued effort of purifying water and, in particular, that of removing radioactive contamination such as U, Ra, and Rn from water [18] should be specially noted because it has been essential for successful observation of low-energy neutrinos.

2. Search for Nucleon Decays

Since the Kamiokande experiment started, a search has been made for nucleon decays with an accumulated exposure of 3.76 kt·y up to November 1988. Here, I do not go into details of the analysis, but interested readers are referred to Ref. [1]. The conclusions drawn from this investigation are summarized as follows.

(i) No anomalous excess of candidate events has been observed above the expected atmospheric-neutrino background level.

(ii) Consequently, there is as yet no evidence for nucleon decay.

The 90% confidence level (CL) lower limits on the nucleon partial lifetime τ/B for various decay modes (τ is the nucleon lifetime and B the branching fraction to the studied decay mode) obtained are shown in Fig. 2 together with the results from the IMB [19] and Frejus [20] experiments. Below, some interesting decay modes are discussed further.

The decay mode $p \to e^+\pi^\circ$ is important if the proton decay is mediated by superheavy gauge bosons, and in a naive SU(5) GUT this decay mode dominates. Experimentally, this decay mode is easy to detect because of the existence of three showering particles and is free of background. Therefore, each proton-decay experiment gives its best τ/B limit among various decay modes studied :

IMB-I+II	(4.4 kt·y)	$\tau/B > 3.1 \times 10^{32}$ y	(90% CL, Ref.[19])
Kamiokande-I+II	(3.57 kt·y)	$\tau/B > 2.5 \times 10^{32}$ y	(90% CL, Ref.[1])
Frejus	(1.4 kt·y)	$\tau/B > 0.51 \times 10^{32}$ y	(90% CL, Ref.[20]).

There are no candidate events observed for this decay mode with each detector. Therefore the combined lower limit is simply given by

$$(\tau/B)_{\text{combined}} > 6.1 \times 10^{32} \text{ y (90\% CL)}.$$

According to the minimal SU(5) prediction [21]

$$(\tau/B)_{\text{minimal SU(5)}} = 4 \times 10^{29\pm0.7} \left(\frac{M_X}{2 \times 10^{14}\text{GeV}}\right)^4 \text{y},$$

where $M_X = (2.0^{+2.1}_{-1.0}) \times 10^{14}$ GeV. Clearly, the minimal SU(5) GUT has been ruled out.

Nucleon decay is also mediated by Higgs scalars. In supersymmetric (SUSY) GUTS the gauge-boson-mediated nucleon decay has several orders of magnitude longer lifetime because of a higher GUT mass scale. This brings the gauge-boson-mediated nucleon-decay modes practically impossible to observe. Instead, the Higgs-mediated nucleon-decay modes $p \to \bar{\nu}K^+$ and $n \to \bar{\nu}K^\circ$ become dominant in SUSY GUTS. For $p \to \bar{\nu}K^+$ the 90% CL background-subtracted lower limit on the partial lifetime obtained by the Kamiokande-I+II experiment [1] is $\tau/B > 9 \times 10^{31}$ y, while that obtained by the Frejus experiment [20] is $\tau/B > 1.5 \times 10^{31}$ y. The difference between the lower limits on τ/B for $p \to \bar{\nu}K^+$ obtained by the Kamiokande and Frejus experiments is more than simply expected from the exposures of both experiments. The reason for this is the following. In $p \to \bar{\nu}K^+$ the dominant K^+ decay mode is $K^+ \to \mu^+\nu$ where μ^+ has low kinetic energy. The Kamiokande detector has a good detection efficiency ($\varepsilon \cdot B_m = 0.48$ where ε is the detection efficiency and B_m is the branching ratio of the K decay mode concerned) for this low-energy muon owing to its good light-collection efficiency (20%). The Frejus detector, on the other hand, has a low detection efficiency ($\varepsilon \cdot B_m = 0.075$) for $K^+ \to \mu^+\nu$ [20]. This fact is reflected on the very different lower limits on τ/B for $p \to \bar{\nu}K^+$ obtained by the two experiments. For $n \to \bar{\nu}K^\circ$, the 90% CL background-subtracted lower limits on τ/B are 8.2×10^{31} y (Kamiokande-I+II) [1] and 1.5×10^{31} y (Frejus) [20]. Here also the good detection efficiency of the Kamiokande detector ($\varepsilon \cdot B_m = 0.10$ for $K^\circ \to 2\pi^\circ$ and 0.07 for $K^\circ \to \pi^+\pi^-$) compared with the Frejus detector [20] ($\varepsilon \cdot B_m = 0.07$ for $K^\circ \to 2\pi^\circ$ and 0.03 for $K^\circ \to \pi^+\pi^-$) is to be noted.

3. Observation of solar neutrinos

Over two decades the only experimental observation of solar neutrinos has been conducted by Davis, Jr. and his collaborators [22,23] using the capture reaction $\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$ with 615 tons of C_2Cl_4. This ^{37}Cl experiment is sensitive mainly to the solar ^{8}B neutrinos. The average neutrino capture rate for a period between March 1970 and March 1988 is reported [23] to be 2.33 ± 0.25 SNU, which is compared to the standard-solar-model (SSM) prediction [24] of 7.9 ± 2.6 SNU. Thus, the Davis' results account for only $1/3 \sim 1/4$ of the SSM prediction. This deficit is the famous solar-neutrino problem.

At Kamioka a real-time observation of solar ^{8}B neutrinos had been pursued with the upgraded Kamiokande-II detector since 1985, and the first result for a finite flux value was reported in 1988 [25]. In the Kamiokande water-Cherenkov detector solar neutrinos are detected *via* elastic scattering $\nu_e e^- \to \nu_e e^-$. The recoil electron in this reaction preserves the neutrino direction within uncertainties mainly arising from multiple scattering in water, and this directionality is the key ingredient of the experiment. This greatly helps identify the solar neutrino signal from the low-energy background due to γ-rays emitted from the surrounding rock, β-rays from spallation products caused by high-energy cosmic-ray muons, and β-rays from ^{214}Bi which is a daughter of ^{222}Rn dissolved in water. (It should be noted at this point that the Davis' ^{37}Cl experiment does not directly mean the detection of the solar neutrinos because that experiment has no directional information. The observed excess ^{37}Ar production above the background level could, in principle, be due to something else.)

The first result from the Kamiokande solar neutrino observation [8,25] was obtained with the following detector performance and operational conditions (corresponding to the last part of the observation period): a fiducial volume of inner 680 tons, live time of 450 days during the observation period between January 1987 and May 1988, trigger threshold of 6.7 MeV (8.8 MeV) at 50% (90%) efficiency, an angular resolution with respect to the neutrino direction of 28° and an energy resolution of 22 %, both at an electron energy E_e of 10 MeV. The energy region for data analysis was taken to be $E_e \geq 9.3$ MeV. Figure 3(a) shows the angular distribution of the events survived various cuts to remove background events, with respect to the direction pointing from the sun to the earth. The solid line in this figure shows the prediction of the SSM [24]. A clear forward peak is observed indicating the evidence of the solar-neutrino detection, but its magnitude is less than the SSM prediction. The observed signal level has been determined by a maximum likelihood technique assuming the shape of energy and angular spectrum as predicted by the SSM with a flat background distribution. The result for the solar ^{8}B neutrino flux $\phi_\nu(^8\mathrm{B})$ is

$$\phi_\nu(^8\mathrm{B}) \quad = \quad (0.46 \pm 0.13 \pm 0.08) * \mathrm{SSM},$$

It should be noted that the SSM prediction of the ^{8}B neutrino flux is $5.8 \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with an effective 3σ uncertainty of $\pm 37\%$.

The Kamiokande-II result is the first direct evidence of neutrinos really coming from the sun. Meanwhile, Davis presented [23] the result of his experiment during the period between August 1986 and March 1988, which corresponds to the Kamiokande-II observation period. The average solar neutrino flux observed during this period was 4.2 $\pm$ 0.7 SNU. Thus, it can be concluded that the results of the Kamiokande-II and the Davis experiments are mutually consistent in essentially the same observation period, and these results seem to indicate that there certainly exists the solar ^{8}B neutrino deficit problem, although the deficit now seems to be about half of the ^{8}B neutrino flux predicted by SSM rather than $1/3 \sim 1/4$.

In June 1988 the detector performance of Kamiokande-II was improved by doubling the PMT gain. The effects of the PMT gain increase are (i) improved energy resolution for low-energy electrons (19.5% at 10 MeV) and (ii) improvement in the event vertex reconsruction. These improvements were achieved owing to the increase (~20%) of hit PMT's corresponding to unit deposited energy by electrons, and led to a significant reduction of the background events. The trigger threshold was lowered to 6.1 MeV (7.9 MeV) at 50 % (90 %) efficiency, and the energy region for the data analysis was extended down to 7.5 MeV.

Figure 3(b) shows the angular distribution of candidate solar-neutrino events observed after the PMT gain increase in the observation period of June 1988 through April 1989, corresponding to a live time of 288 days. The solid line shows the SSM prediction. The solar ^{8}B neutrino flux obtained is

$$\phi_\nu(^8\mathrm{B}) \quad = \quad (0.39 \pm 0.09 \pm \sim 0.06) \; * \, \mathrm{SSM},$$

Note that the statistical error here is already less than that of our previous result even though the observation period is significantly shorter than before. This new result is statistically consistent with the previous one, which indicates no strong time variation of the solar ^{8}B neutrino flux within the statistical errors during our entire observation period of January 1987 through April 1989.

The Kamiokande-II observation of the ^{8}B solar neutrino flux has been continuing. Further efforts to reduce the background are also being made, particularly by improving the analysis software. The problems which can be addressed include the possible long-term variation of the flux, day-night asymmetry, seasonal variation, and energy spectrum of recoil electrons. The first one is related with the solar physics or solar cycle, and the rest of the problems with neutrino oscillation either in vacuum or in matter. However, the statistical accuracy will be limited with the present Kamiokande detector. This gives a strong motivation for constructing the Superkamiokande detector.

4. Future of the Kamioka Underground Experiment

As already noted, the Superkamiokande project with a 50,000 ton water Cherenkov detector has been proposed (see Fig. 1 and Table II). The budget request to the Ministry of Education, Science and Culture started in Japanese fiscal year 1988, but it has not yet been approved. Once the govermental approval is gained, the detector will be constructed in five years. In the rest of this section, the physics capabilities of the Superkamiokande will be discussed on the three topics, the search for nucleon decays, observation of solar neutrinos, and detection of stellar-collapse neutrinos. Those for other topics such as the observation of atmospheric neutrinos etc. are discussed in Refs. [26,27].

Whether the next-generation detectors for the nucleon-decay search such as Superkamiokande can make significant contribution depends on the capability of rejecting background due to atmospheric neutrinos. In this regard, each of the Kamiokande, IMB, and Frejus groups has investigated the atmospheric-neutrino background level in its detector by a Monte Carlo simulation. The results for the decay mode $p \to e^+\pi^\circ$ are:

Kamiokande-II [1]	simulated 105 kt·y,	background < 0.02 ev/kt·y at 90% CL
IMB-III [28]	simulated 40 kt·y,	background < 0.06 ev/kt·y at 90% CL
Frejus [28]	simulated 75 kt·y,	background < 0.03 ev/kt·y at 90% CL.

Since Superkamiokande is planned to have better light-collection efficiency (40%) than Kamiokande-II, the lower limit of $\tau/B(p \to e^+\pi^\circ)$ would be easily pushed up to $\sim 10^{34}$ y. It should also be mentioned that with the Kamiokande-II simulation of 105 kt·y [1], there are several other decay modes which are still background free (<0.02 ev/kt·y at 90% CL), i.e., $p \to e\eta(\gamma\gamma)$, $e\eta(3\pi^\circ)$, $eK^\circ(2\pi^\circ)$, $e\omega(\gamma\pi^\circ)$, $\mu\pi^\circ$, $\mu\eta(\gamma\gamma)$ and $\mu\eta(3\pi^\circ)$. The expected lower limits on the partial lifetime for various nucleon decay modes to be obtained in five years of the Superkamiokande operation (110 kt·y) are shown in Fig. 1. It is seen that a partial lifetime limit of 10^{33-34} years is expected for several decay modes. If the nucleon has a lifetime of less than 10^{34} years, one has a good chance with Superkamiokande to observe its decay. Otherwise, still one can obtain strong constraints on the Grand Unified Theories.

To solve the solar-neutrino problem various theoretical possibilities have been proposed. One main stream is to lower the temperature of the sun's core by departing from the SSM. The other stream is to ask an answer in the properties of the neutrino such as the neutrino oscillations either in vacuum or in matter and a finite neutrino magnetic moment. This latter stream is very interesting from the particle-physics viewpoint. Hints of the neutrino oscillations may be obtained from measurements of the shape of the neutrino (or recoil-electron) energy spectrum, and day-night and seasonal variations of the ^{8}B solar neutrino flux. Note that these objects are not affected by the solar physics. Another interesting object to study is the possible time dependence of the ^{8}B solar neutrino flux correlated with the solar cycle. Davis [23] has claimed a hint of such a correlation in his data. If such a correlation is really found, the most natural explanation is given by the neutrino's magnetic moment, on which, however, a severe restriction has been placed by the observation of neutrinos emitted by the SN1987A [29].

In any case, high statistics are needed for such measurements to give significant results. The Superkamiokande will have the required high counting rate, because an expected rate of the ^{8}B solar neutrino events is ~20/day, which is constrasted with ~0.25/day with the present Kamiokande-II detector. This great improvement in sensitivity will be achieved by the two factors, large fiducial mass and low trigger threshold. The ^{8}B solar neutrino flux will be measured yearly with a statistical accuracy of $\pm(1 \sim 2)\%$ and a systematic error of $\leq 2\%$. With a detector live time of one year the day/night and seasonal variations of the flux can be measured to an accuracy of $\pm(2 \sim 3)\%$. Figure 4 shows the energy spectra of recoil electrons for several assumptions on the neutrino oscillation parameters, where the expected statistical accuracy of the data corresponding to a detector live time of one year is also indicated.

Let me turn to the final topic, the detection of supernova neutrinos. If a type-II supernova explosion occurs at the center of our galaxy, a total of $\sim$ 4000 neutrino events will be detected by Superkamiokande. These events include $\sim$ 130 ν_e events of which $\sim$ 10% is due to the neutronization burst, and $\sim$ 80 $\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$ events. With this large statistics, the detailed information on the formation process of a neutron star will be obtained. From the $\nu-e$ elastic scattering events, the direction of the supernova will be determined with an accuracy of $\sim 2°$. The mass limit for ν_e will be improved down to $1 \sim 2$ eV using the ν_e events from the initial $\sim$ 10 ms neutronization burst. The time distribution of the $\nu-e$ elastic scattering events will allow measurement of the ν_μ and ν_τ masses in the range of 200 eV - 30 keV. If $<E_{\nu_\mu}>=<E_{\nu_\tau}>\approx 2<E_{\nu_e}>$ as predicted by Mayle, Wilson and Schramm [30], this difference in the mean energy for different neutrino species can be exploited to determine (or limit) the ν_μ and ν_τ masses down to $\sim$ 50 eV. These expectations clearly demonstrate the great capabilities of Superkamiokande in supernova physics as well as in neutrino physics, once a type-II supernova explosion occurs at the center of our galaxy. There is a rather broad range of prediction for the type-II supernova rate in our galaxy, i.e., 1/(10$\sim$50 y). Nevertheless, there will be a good chance for Superkamiokande to observe a type-II supernova burst in our galaxy during its expected life of $\sim$ 20 years.

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Table I. Summary of the physics results from Kamiokande-I and -II.

Subject	Main results	Comments	References
Nucleon decay	$\tau/B(e^+\pi^0)>2.6\times10^{32}y$ $\tau/B(\bar{\nu}K^+) > 1.0\times10^{32}y$	exposure 3.76kt•y	[1]
n-$\bar{n}$ oscillation	$\tau_{n\bar{n}}>1.2\times10^8 s$ $T(^{16}O)>4.3\times10^{31}y$	exposure 1.1kt•y	[2]
GUT magnetic monopole (Rubakov effect in the sun)	$\phi_M(\sigma_0/1mb)<1.6\times10^{-21}$ $\times(\beta_M/10^{-3})^2 cm^{-2}s^{-1}sr^{-1}$	$\langle E_\nu\rangle\sim35$ MeV live time 335 d	[3]
Atmospheric ν	ν_μ deficit $(\nu_\mu/\nu_e)_{Data}/(\nu_\mu/\nu_e)_{MC}$ $=0.59\pm0.07$	$p_e=30\sim1330$ MeV/c $p_\mu=205\sim1500$ MeV/c exposure 2.87kt•y ν_μ polarization effect not included but does not change the result significantly	[4]
Stellar collapse ν	SN1987A 11 events in 13 sec	1987 February 23 "The only successful result of GUT" — L. Alvarez	[5,6]
ν from past supernovae	$\phi_{\bar{\nu}_e}<226 cm^{-2}s^{-1}$ (3ev., $19<E_\nu<35$ MeV)	live time 450 days	[7]
^{8}B solar ν	$\phi_{\nu_e}(^8B)$/S.S.M. $=0.46\pm0.13\pm0.08$ $\phi_{\nu_e}(^8B)$/S.S.M. $=0.39\pm0.09\pm0.06$(prel.)	Jan '87 - May '88 450 d, $E_\nu\geq9.3$ MeV Jun '88 - Apr '89 288 d, $E_\nu\geq7.5$ MeV (PMT gain doubled)	[8] [9]
Solar flare ν	$\phi_{\nu_e}<3.5\times10^7/cm^2$/flare $<1.4\times10^7/cm^2$/flare (at $E_\nu\geq100$ MeV)	for Importance 4 for Importance 3	[10,11]
WIMPs ($\chi\bar{\chi}$ annihilation in the sun)	$m_{\nu D}, m_{\tilde{\nu}e}, m_{\tilde{\nu}\mu}>3$ GeV excluded $m_{\tilde{\nu}\tau}>4$ GeV excluded	$m_{\tilde{\gamma}}$: not limited $m_{\nu M}$: marginal	[12]
HE μ from Cyg X-3	$\phi_\mu<2.2\times10^{-12}cm^{-2}s^{-1}$ $<1.9\times10^{-11}$ $<2.1\times10^{-11}$	Jul '83 - Sep '84 Oct '83 Oct '85	[13] [14]
HE ν_μ from SN1987A (upgoing μ)	$\phi_{\nu\mu}<2.4\times10^{-5}cm^{-2}s^{-1}$ $<2.3\times10^{-3}cm^{-2}s^{-1}$	first 6 months $E_c=10^{15}$eV, $\gamma=2.1$ $E_c=10^{12}$eV, $\gamma=2.7$	[15]
HE ν_μ from point sources (upgoing μ)	$\phi_{\nu\mu}<1.7\times10^{-5}cm^{-2}s^{-1}$ $<5.4\times10^{-6}cm^{-2}s^{-1}$	Jul '83 - Mar '88 Cyg X-3 LMC X-4	[16]
Cosmic-ray μ polarization	$P_\mu=0.28\pm0.09$ (preliminary)	$1.1\sim10$ TeV	
Cosmic-ray μ anisotropy		under study	

Table II. Parameters of the present Kamiokande-II detector (as of August 1989, see Ref.[9]) and the planned Superkamiokande detector.

	Kamiokande-II	Superkamiokande
outer dimensions	19m (ϕ)× 16m(h)	38m(ϕ)× 40m(h)
total mass	4,500t	50,000t
sensitive mass	2,140t	32,000t
fiducial mass	1, 040t [a] (680t [b])	22,000t
number of PMT's	948	11,076
..(inner detector)		
density of PMT's	$1/m^2$	$2/m^2$
light collection efficiency	20%	40%
thickness of antilayer	1.2~1.7m	2m
energy resolution	$0.04/\sqrt{E(GeV)}$ [c]	$0.03/\sqrt{E(GeV)}$ [c]
..for electrons	$0.195/\sqrt{E/10MeV}$ [d]	$0.16/\sqrt{E/10MeV}$ [d]
vertex resolution	1.2m	0.5m
..for 10MeV electrons		
trigger threshold	6.1MeV	<5MeV
analysis threshold	7.5MeV	5MeV

[a] For the nucleon decay analysis (see Ref.[1]).

[b] For the solar neutrino analysis (see Refs.[8,9]).

[c] From the observed number of photoelectrons.

[d] From the number of hit PMT's; only applicable for the analysis of low-energy electrons.

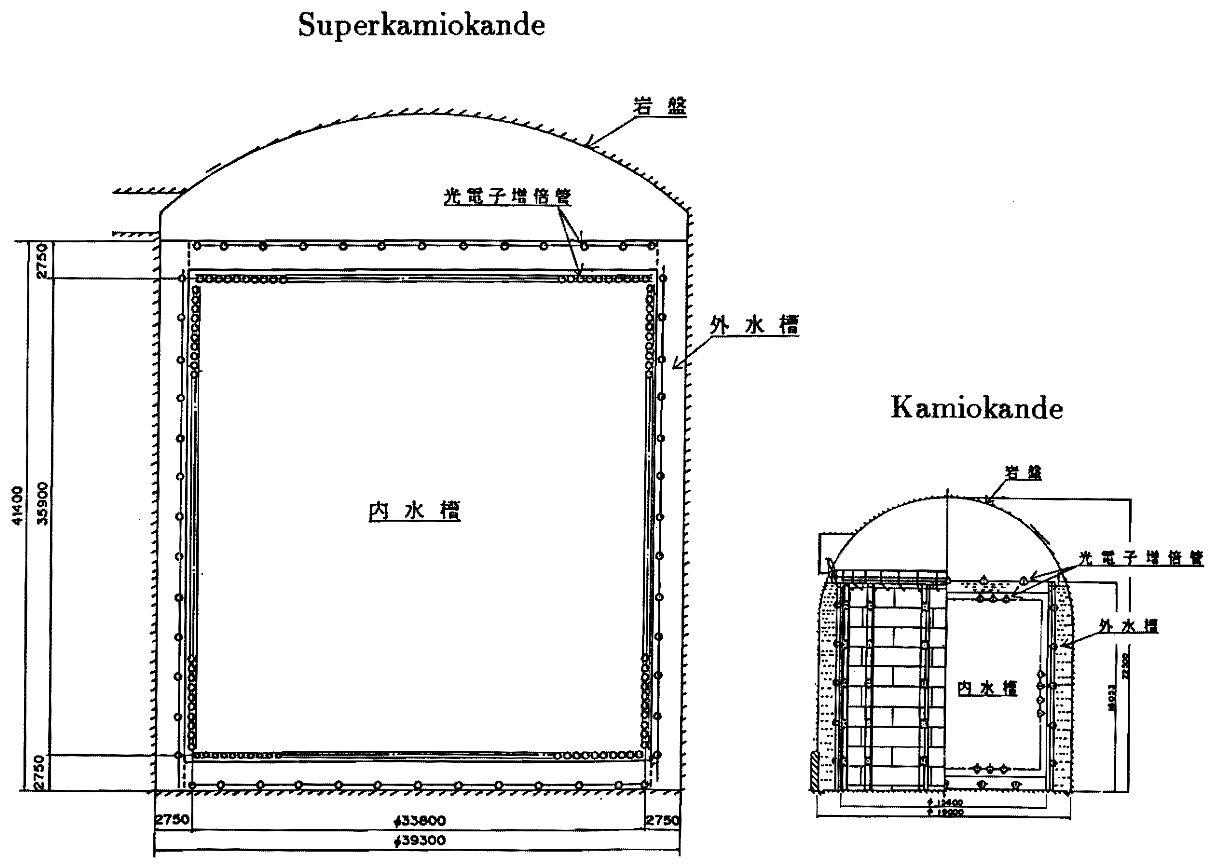

Fig. 1. Comparison of the present Kamiokande detector and the proposed Superkamiokande detector.

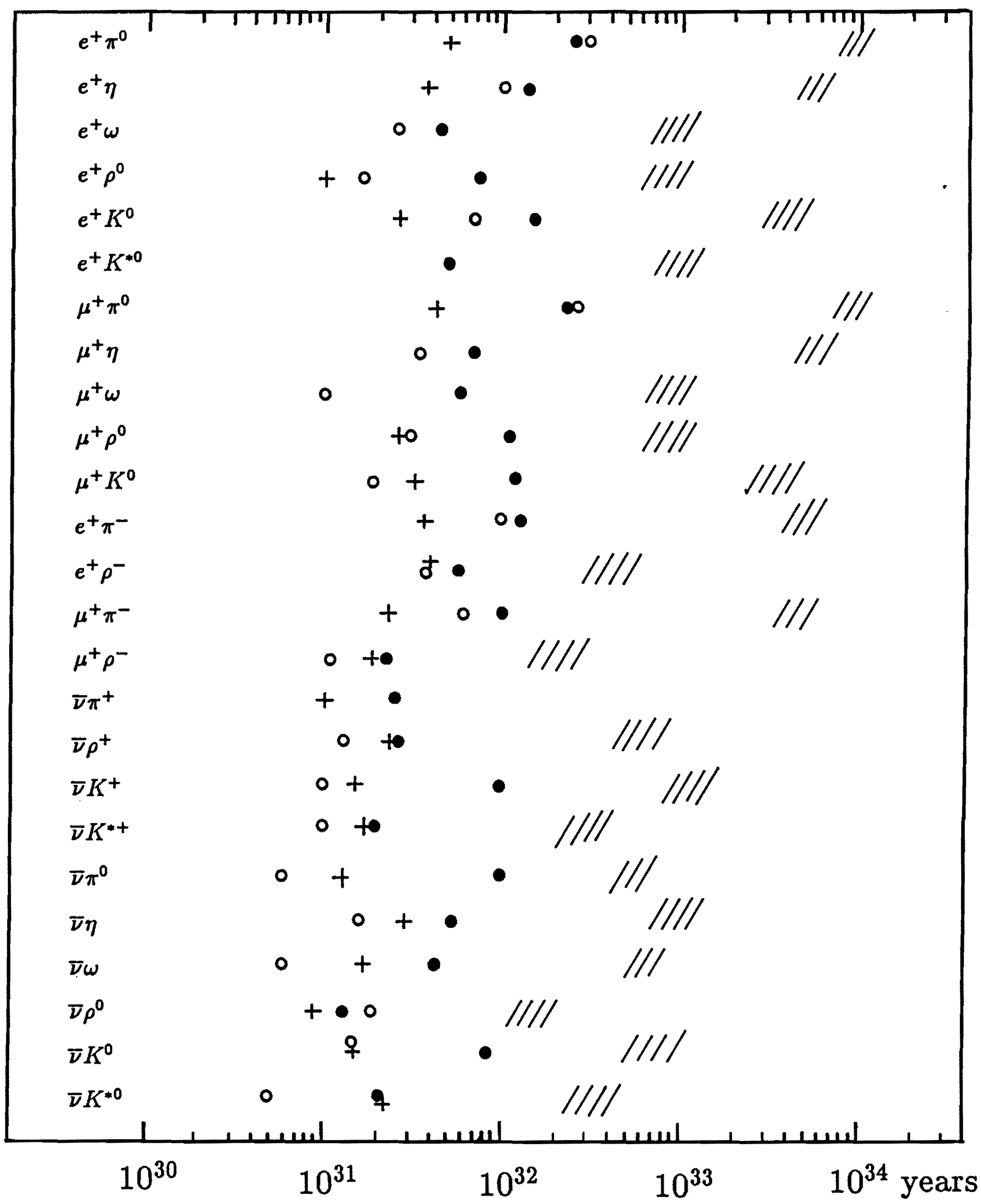

Fig. 2. The 90 % confidence level lower limits of the nucleon partial life time for various nucleon decay modes obtained by the Kamiokande (filled circles), IMB (open circles), and Frejus (pluses) experiments. The expected limits to be reached after 5 years of the Superkamiokande operation are also shown by the hatches. [Taken from Ref. 27.]

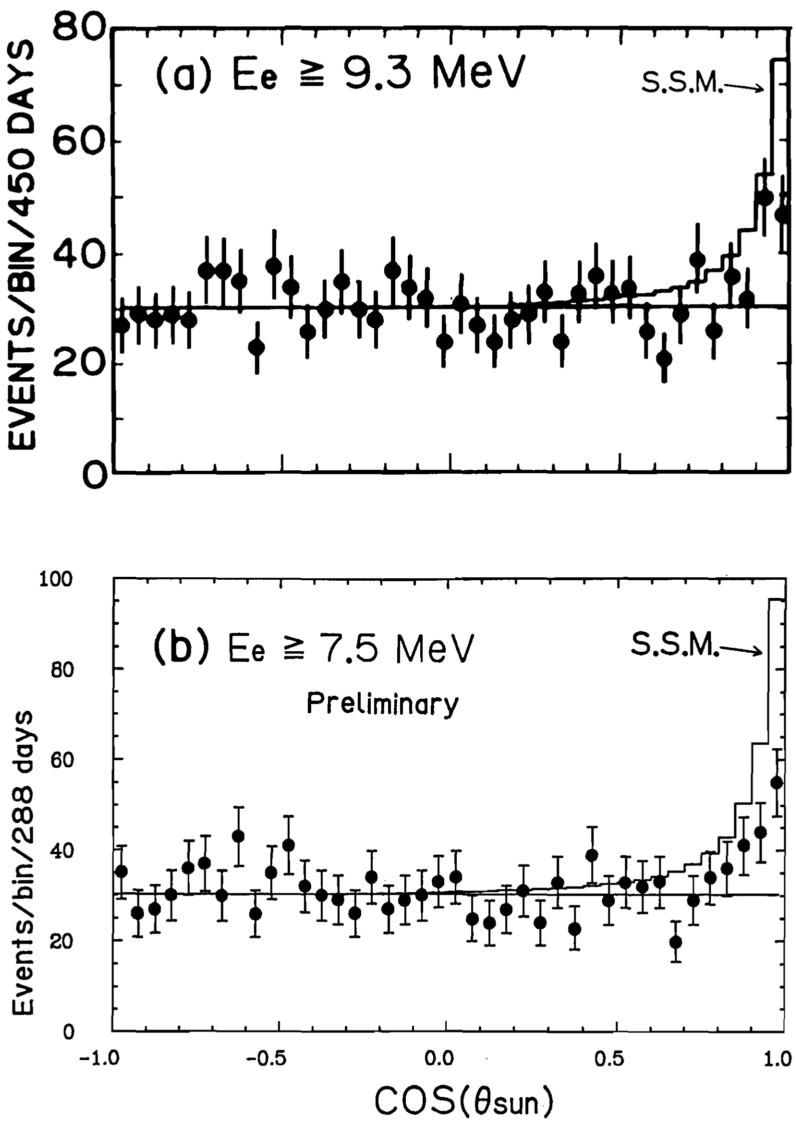

Fig. 3. Distributions in $cos\theta_{sun}$, the cosine of the angle between the trajectory of an electron and the direction pointing from the sun to the earth at a given time. (a) 450 days of data during the observation period January 1987 - May 1988, with $E_e \geq 9.3$ MeV. (b) 288 days of data during the observation period June 1988 - April 1989, with $E_e \geq 7.5$ MeV.

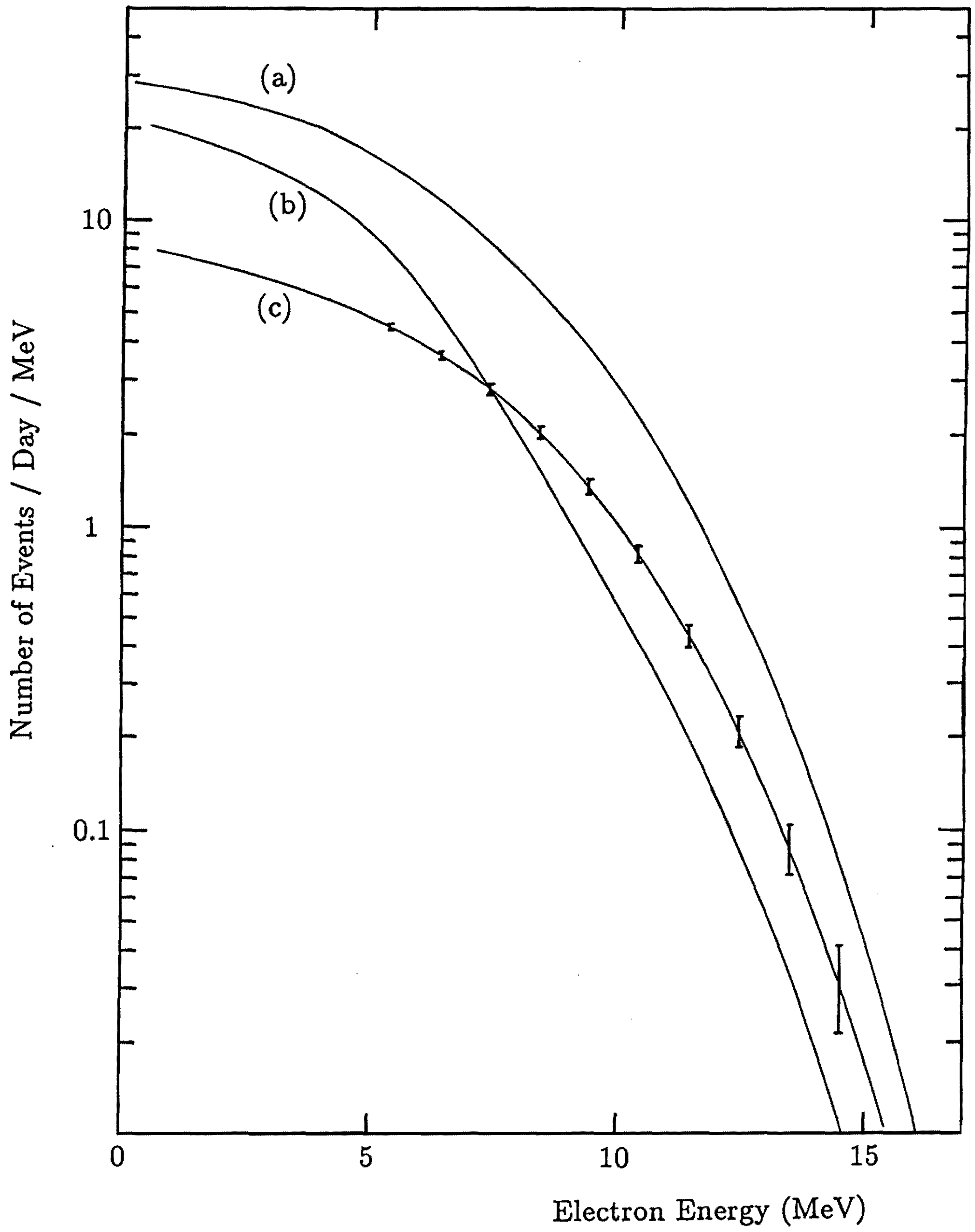

Fig. 4. Recoil electron energy spectra for three cases. (a) No oscillations. (b) $\Delta m^2 = 1.3 \times 10^{-4}$ eV^2, $\sin^2 2\theta = 0.01$. (c) $\Delta m^2 = 6.0 \times 10^{-6}$ eV^2, $\sin^2 2\theta = 0.01$. [Taken from Ref. 27.]