RESULTS FROM THE KAMIOKA NUCLEON DECAY EXPERIMENT

KAMIOKANDE Collaboration*

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ABSTRACT

During a live time of 201 days eighty events were observed in the Kamioka nucleon decay experiment, with event vertices contained in a fiducial volume of 880 tons. Most of the events can be well interpreted as due to ν interactions and the limits of τ/B already exceed 10^{31} years(90% C.L.) for most of the possible decay modes. Two candidate events were found after a tight kinematical cut while expected backgrounds are small.

I. INTRODUCTION

A large water Cerenkov detector was constructed and in operation at Kamioka, Japan since July, 1983. The primary aim of the experiment is to detect possible nucleon decay, which is naturally predicted in grand unification theories. The unprecedented photo-sensitivity of this detector is extremely powerful to study the nucleon decay modes in detail. This aspect is very important because the expected nucleon decay modes are widely different among various versions of grand unification schemes.

The principal background comes from interactions of ν's produced in the atmosphere by primary cosmic rays. High photo-sensitivity of the detector also serves to reduce background thanks to excellent resolutions of event topology, kinematic quantities, etc. This report describes results of the first 201 days of observation after a brief introduction of the detector.

II. DETECTOR

The KAMIOKANDE detector(Fig.1) is located 1000m underground(2700 mwe) in the Kamioka metal mine, about 300km west of Tokyo, 25.8° N geomagnetic latitude. It is a large cylindrical volume of water, 15.6mϕ x 16mh, 3000 tons, viewed by 1000 photomultipliers with 20" photosensitive area, covering 20% of the entire inner surface of the tank. The fiducial volume is defined to be at least 2m inside from the PMT planes and is 880 tons in mass. The gain of each PMT is adjusted, using 0.6 GeV/c π^- at KEK as well as a Xe flash lamp system. Its r.m.s. spread is less than 8%. The long term stability of PMTs is constantly monitored with an Ar flash lamp + scintillator ball system and also by measuring the pulse height of cosmic ray muons penetrating vertically. The gain has been stable within 2% from July 1983 to April 1984. The water transparency is also constantly monitored and the attenuation length averaged over PMT photosensitive region is more than 35m. The absolute normalization(i.e. photoelectron yield per unit energy deposition) is therefore stable and is known to be 3.8 ± 0.3 photoelectrons/MeV.

The trigger is essentially made by asking for at least 110 photoelectrons in all PMT, which corresponds to 30MeV for electrons.
This trigger is quite general and the trigger efficiency is almost 100% for most of the nucleon decay channels. The trigger rate is 1/2sec, about 70% being cosmic ray muons.

The sum signal of the 1000 PMTs is digitized and recorded up to 100

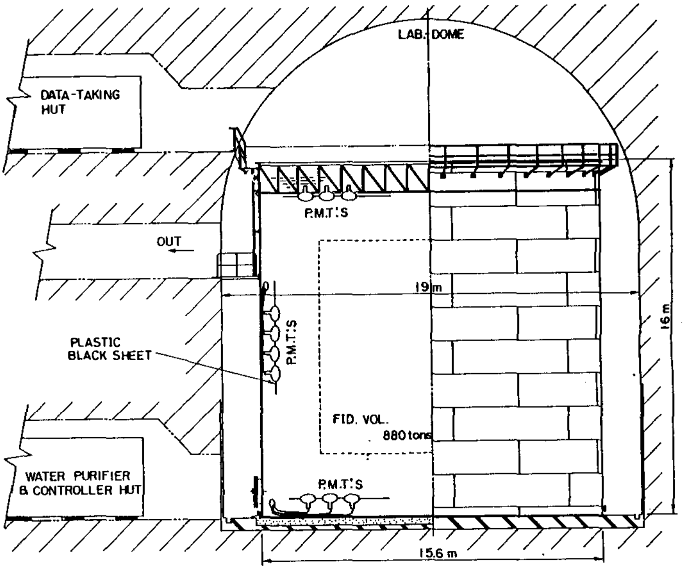

Fig.1 KAMIOKANDE detector

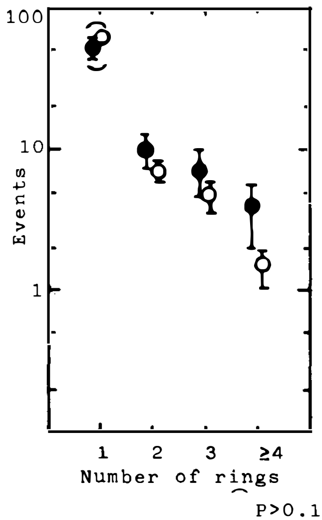

Fig.2
Ring multiplicity distribution. Full circles: data, Open circles: expected for ν interactions

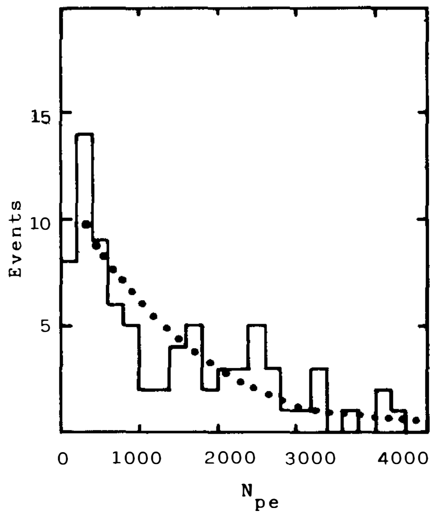

Fig.3 Total photoelectron distribution. Dotted curve is expected from ν interactions

μsec by two transient digitizers. $\mu \to e$ decay signals are then clearly identified by looking at the second pulses and the efficiency is found to be 70%. The great sensitivity of the detector enables us to make detailed analyses on an event-by-event basis, e.g. to count multiplicity of Cerenkov rings, and to measure their directions and energies by performing the space reconstruction. This information is quite powerful to pick up possible nucleon decay candidates as well as to reject cosmic ray ν backgrounds by, for example, imposing kinematical constraints.

III. ANALYSIS

The KAMIOKANDE detector was fully ready in July 1983 and the data-taking began on July 6,1983. We have so far accumulated and analysed data up to April 5,1984, corresponding to 201 days of live time and 485 ton•years or $2.9 \cdot 10^{32}$ nucleon years. $8.7 \cdot 10^{6}$ of total triggers are subject to the reduction process, which rejects penetrating cosmic ray μ , accidentals, external electric noises and cosmic ray μ which clip the edges of the tank. The reduction rate is altogether 1.1%. The remaining $8.9 \cdot 10^{4}$ events, scanned by two independent groups of physicists and after space reconstruction, finally reduce to 80 events with event vertices contained in the fiducial volume. Out of 80 events, 59 events have single Cerenkov rings and 21 events two or more Cerenkov rings. The ring multiplicity distribution is shown in Fig.2. They are of course not all nucleon decay candidates but mostly from ν interactions. A detailed Monte Carlo program was developed to simulate ν interactions, taking into accound the cosmic ray ν flux[1], ν -cross sections[2] and nuclear effects in O^{16} nuclei[3].The comparison is then made and shown in the same figure. Agreement is good. The total photoelectron distribution of all events is displayed in Fig.3. The single ring events are divided into Shower-type(S-type) and Meson-type (M-type) events. This is possible by measuring diffuseness of Cerenkov rings, namely electromagnetic showers have more multiple scattering than muons or charged pions,thus producing more diffuse rings. Fig.4 shows how well the S/M-type can be identified. Fig.5 shows momentum distributions of the M- and S-type single ring events. As seen in Fig.3 and 5, the distributions are also compared with expectations and the agreement is good. Therefore the general feature of the data is well explained by ν interactions.

In order to further reduce the ν backgrounds and to pick up possible nucleon decay candidates, the following selections are performed:

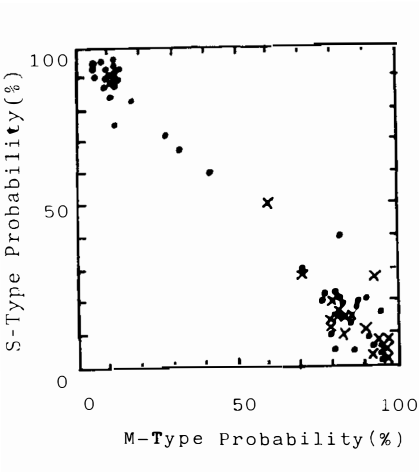

Fig.4 M/S type separation for single ring events. Crosses are those with μ→e signals.

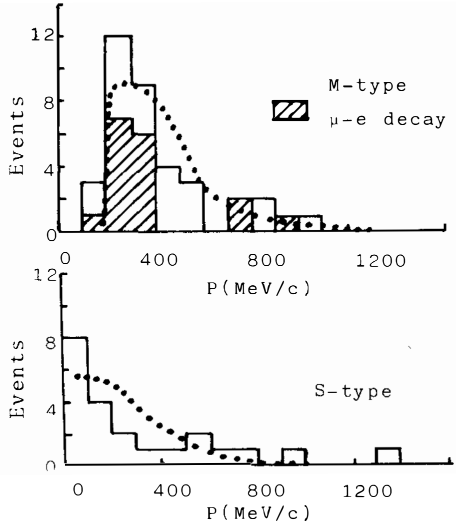

Fig.5 Momentum distribution of M-type and S-type single ring events. Dotted curves are expected from ν interactions

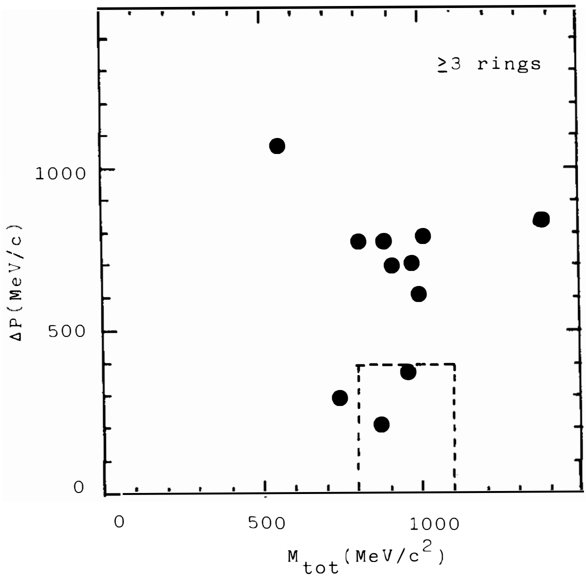

Fig.6 ΔP vs M_{tot}. Two events within the dotted square are possible candidates of $N \to \ell^+ \chi$

(A) For 1-ring events, which might contain $p \to \nu k^+ (\nu\mu^+)$ or $p \to \nu\pi^+$ candidates, we require M-type, $\mu \to e$ signal and $226 < P_\mu < 246$ MeV/c for $p \to \nu k^+ (\nu\mu^+)$. Similary we require M-type and $400 < N_{pe}(\text{ring}) < 700$ for $p \to \nu\pi^+$. $N_{pe}(\text{ring})$ is the number of photoelectrons in the Cerenkov ring. A wide regin of N_{pe} (ring) must be used, since π^+ momenta are distorted due to nuclear interactions of π^+ with water.

(B) For 2-ring events, which might contain $N \to \ell^+ X$, $X = \pi^-, \ldots,$ We consider rings with more than 50 photoelectrons only. Then the opening angle between 2 rings, $\theta_{op} > 120°$, and $\mu \to e$ signals must exist for $N \to \mu^+ X$. This simple criteria is, at present, sufficient to kill all the 2-ring events.

(C) For 3 or more ring events, which might contain $N \to \ell^+ X$, $X = \pi^0$, $\rho^-, \ldots,$ we can impose tighter kinematic constraints, namely, by assigning particle species(e/γ, μ or π) to each ring we calculate the total invariant mass M_{tot} and the total residual momentum Δp, and then impose $800 < M_{tot} < 1100$ MeV/c^2 and $\Delta p < 400$ MeV/c. The particle assignment which satisfies these criteria must then be consistent with M/S-type if the M/S-type can be identified. We further require that the invariant masses of the mesons be $600 < M_\rho < 900$, $600 < M_{\omega, K^*} < 1000$, $400 < M_K \leq 600$, $500 < M_\eta < 650$, $100 < M_{\pi^0} < 200$ MeV/c^2. $\mu \to e$ signals are required for $N \to \mu^+ X$. In Fig.6 we plot Δp vs M_{tot}, one point for each event, of a particular particle assignment which gives minimum $|M_{tot} - M_p| + \Delta p$. One sees 2 events satisfy the Δp-M_{tot} cut. These events will be discussed below.

(D) for $N \to \nu X$ other than $p \to \nu k^+, \nu\pi^+$, we do the similar analyses but will not describe them here.

Exactly the same analyses are applied to the artificial data simulating ν-interactions so as to estimate ν backgrounds.

The detection efficiencies are obtained by doing the same analyses to the simulated nucleon decay data. The results for various decay modes are listed in Tables 1 and 2, in which lower limits on τ/B, nucleon lifetime/branching ratio, are calculated without subtracting the estimated backgrounds. One sees most of τ/B already exceed 10^{31} years(90% C.L.).

IV. TWO CANDIDATE EVENTS

We see from Table 2 that the number of events after selection is quite consistent with ν backgrounds for $N \to \nu X$ modes. On the other hand the tight selection cuts eliminate most of ν backgounds from $N \to \ell^{+}X$modes. Two events nevertheless survive the cuts. We show these two events here. Fig.7 shows the exploded view of the first event in which PMT walls are opened top and bottom and also at the side. The area of each circle is proportional to the number of photoelectrons observed by PMT. Three well separated Cerenkov rings are clearly seen. The transient digitizer records a small second pulse but it is just on the boundary between noise and a $\mu \to e$ signal. Existence of μ in the event is therefore ambiguous. The curves in Fig.7 are the results of the fit assuming a common vertex for the rings. Ring 2 and Ring 3 are consistent with M-type and S-type respectively. This event can be interpreted as a nucleon decay in the following modes:

(a) $p \to \mu^{+}\eta(\to \gamma\gamma)$

The particle assignments are Ring 1 = γ, Ring 2 = μ and Ring 3 = γ. Then $M_{\gamma\gamma}$ = 590±100 MeV, M_{tot} = 960±150 MeV, Δp = 360±150 MeV/c.

(b) $p \to \mu^{+}K^{\circ}(\to \pi^{\circ}\pi^{\circ})$

Ring 1 = π°(one of γ's unobserved), Ring 2 = μ and Ring 3 = π°(one of γ's unobserved). $M_{\pi^{\circ}\pi^{\circ}}$ = 600±100 MeV, M_{tot} = 960±150 MeV, Δp = 330±150 MeV/c.

(c) $n \to e^{+}\rho^{-}$

Ring 1 = π°(one of γ's unobserved), Ring 2 = π^{-} and Ring 3 = e^{+}

$M_{\pi^{\circ}\pi^{\circ}}$ = 600±150 MeV, M_{tot} = 1090±150 MeV, Δp = 360±150 MeV/c.

In order to estimate ν backgrounds we generate ν interactions of 2 years equivalent and let them pass through the selection cuts. No events satisfy the cuts.

Fig.8 shows the second candidate event. This event has 5 rings and no $\mu \to e$ signal. M/S-type separation is not possible. When one assigns Ring 1 = e, Ring 2 = π, Ring 3 = γ, ring 4 = γ and Ring 5 = γ, then $M_{\pi\gamma\gamma\gamma}$ = 630±150 MeV, M_{tot} = 890±150 MeV, Δp = 270±150 MeV/c. Thus this event is consistent with $p \to e^{+}\omega^{\circ}$ or $e^{+}\rho^{-}$. We do not take the inconsistency of $\pi\gamma\gamma\gamma$ with ω° or $\bar{\rho}$ seriously due to a high probability of π-water interactions. Expected ν backgrounds are estimated again by generating ν interactions of 2 years equivalent and letting them pass

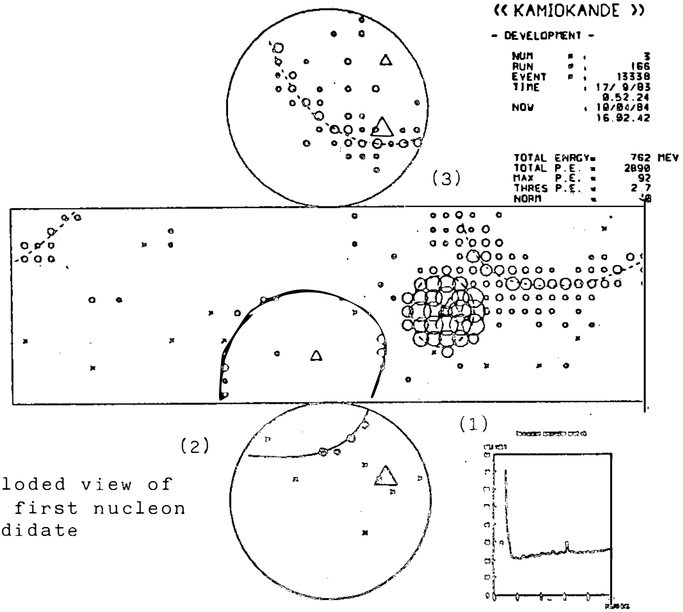

Fig.7 Exploded view of the first nucleon candidate

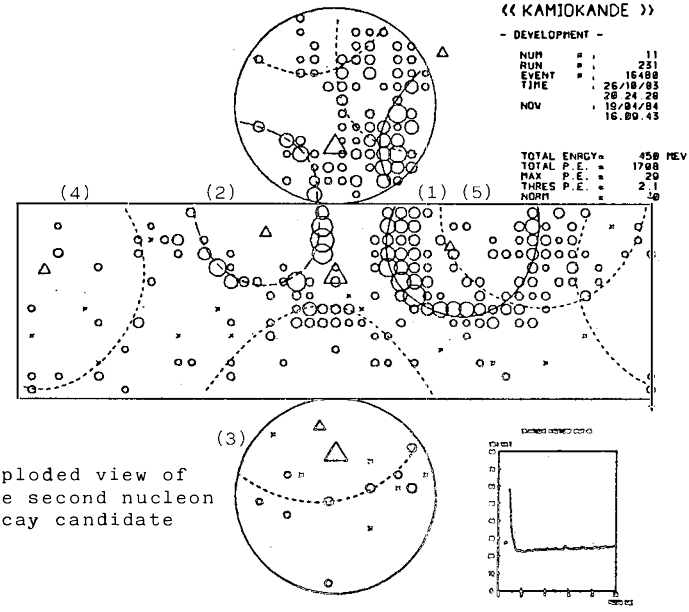

Fig.8 Exploded view of the second nucleon decay candidate

through the analysis program. No event satisfies the cuts for $e^{+}\rho^{-}$, while two events remain after the cuts for $e^{+}\omega^{\circ}$.

V. CONCLUSION

The KAMIOKANDE detector has been operated successfuly since July 6,1983 and the data upto April 5,1984 were analysed, corresponding to 485 ton•years or $2.9 \cdot 10^{32}$ nucleon.years. Their general characteristics can be well explained by ν interactions. Lower limits on τ /B were obtained for a number of possible decay modes and $\tau/B > 10^{31}$ years(90% C.L.) for most of them. Two events survived tighter kinematical cuts while expected ν backgounds are small. They are consistent with $N \to \mu^{+}\eta$ $(\gamma\gamma)$, $\mu^{+}K^{\circ}(\pi^{\circ}\pi^{\circ})$, $e^{+}\rho^{-}$ and $N \to e^{+}\omega$, $e^{+}\rho^{-}$ respectively.

References

1) T.K.Gaisser, Phys.Rev.Lett. 51, 223(1983)
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Table 1. τ/B Lower Limit (90%CL)

$- N \to \ell^{+}X -$

Preliminary

T=201.3days WT=485 ton•years

Decay Modes	ε.Bm	ν-B.G.	Candidates	τ/B(90%CL) x10^{31} years
$P \to e^{+}\pi^{\circ}$	0.45	0	0	3.2
$e^{\circ}\eta$	0.38	0	0	2.7
$e^{+}\omega$	0.29	0.6	1	1.2
$e^{+}\rho^{\circ}$	0.30	0.3	0	2.1
$e^{+}K^{\circ}$ $(2\pi^{\circ})$	0.16	0	0	2.8
$(\pi^{+}\pi^{-})$	0.23	0.3	0	
$e^{+}K^{*}$	0.20	0	0	1.4
$P \to \mu^{+}\pi^{\circ}$	0.39	0	0	2.8
$\mu^{+}\eta_{\circ}(2\gamma)$	0.27	0	1	1.1
$\mu^{+}\rho_{\circ}$	0.31	0	0	2.2
$\mu^{+}K$ $(2\pi^{\circ})$	0.11	0	1	1.1
$(\pi^{+}\pi^{-})$	0.16	0	0	
$n \to e^{+}\pi^{-}$	0.25	0.1	0	1.4
$e^{+}\rho^{-}$	0.20	0	2	0.4
$n \to \mu^{+}\pi^{-}$	0.28	0	0	1.6
$\mu^{+}\rho^{-}$	0.14	0.3	0	0.8

Table 2. /B Lower Limit (90%CL)

– $N \rightarrow \bar{\nu}X$ – Preliminary

T=201.3days WT=485 ton·years

Decay Modes	ε.Bm	ν -B.G.	Candidates	τ/B(90%CL) $\times 10^{31}$ years
$p \rightarrow \bar{\nu}\pi^+$	0.22	9.9	8	0.3
$\bar{\nu}\rho^+$	0.45	1.8	2	1.4
$\bar{\nu}K^+$ $(\mu^+\nu)$	0.28	1.1	2	
$(\pi^+\pi^0)$	0.16	0.2	1	1.1
$\bar{\nu}K$	0.62	2.5	3	1.5
$n \rightarrow \bar{\nu}\pi^0$	0.34	0.2	0	1.9
$\bar{\nu}\eta^0(2\gamma)$	0.27	0	0	1.5
$\bar{\nu}\omega^0$ (a)	0.36	0.6	1	1.2
$\bar{\nu}\rho^0$	0.24	1.0	0	1.4
$\bar{\nu}K^0$ $(\pi^0\pi^0)$	0.12	0	0	
$(\pi^+\pi^-)$	0.10	0.1	0	1.2
$\bar{\nu}K^{*0}$	0.54	2.5	3	1.0

(a) also for $p \rightarrow \mu^+\omega^0$