Table and Figure Captions

Fig. 1.1   The proton-proton reaction chain. Reaction flow and branching ratio are shown.

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Fig. 1.3   Expected solar neutrino spectra at the earth from the SSM [ref 1-5] are shown for each reaction. Solid and dotted lines indicate p-p chain and CNO cycle reactions, respectively. Flux units are [/cm^2/sec/MeV] for continuum and [/cm^2/sec] for line spectra (^{7}Be and pep neutrinos).

Fig. 1.4   Solar neutrino flux observed by ^{37}Cl experiment [ref 1-2] from 1970 (run 18) to 1990 (run 114) is plotted (white circles with error bars) in units of ^{37}Ar production rate (background is not subtracted) and in units of SNU (1 SNU = 10^{-36} captures/atom/sec). Sun-spot numbers (dashed line) are inversely super-imposed with an arbitrary normalization.

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Fig. 4.12 Schematic view of light reflectors installed for Kam-3 is shown. Materials used are also shown.

Fig. 4.13 Vertex resolution for electron as a function of electron total energy is shown. Precise vertex reconstruction was applied to the Monte Calro events for the comparison. Dotted, dashed and solid lines denote Kam-2 gain×1, Kam-2 gain×2 and Kam-3 vertex resolution, respectively.

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Fig. 4.15 Energy resolutions of Kam-2 gain×1 (dots), Kam-2 gain×2 (dashes) and Kam-3 (solid) are shown as a function of electron total energy.

Fig. 4.16 Multi-photon effect on energy resolution is schematically shown. Typical geometry causing vertex dependency of the energy scale is used. Kam-2 (no reflector) observes same number of hits and also same number of photons in both near and far PMT plane. Kam-3 (with reflector) catches larger number of photons due to reflectors, and larger number of hits in the case of far PMT plane, but number of hits in the case of near PMT plane does not increase. Therefore, number of photons will offer better energy resolution in ideal case (if we can count number of photons correctly), but number of hits will not improve energy resolution so much.

Fig. 4.17 Typical Cherenkov ring image of 10 MeV electron is shown by a perspective drawing and exploded view. Ideal (opening angle is 42°) Cherenkov ring is shown in the perspective drawing. Hit PMT is shown by a circle and the size of the circle is proportional to its pulse height.

Fig. 4.18 On-line data flow is schematically shown. Time and charge information are acquired by micro VAX-II on-line computer through CAMAC interface. The data is first stored and accumulated in the disk system, and then they are transmitted to a VAX station 3800 outside of the mine through an optical link and written to 3480-CMT.

Fig. 4.19 Signal processing in the ATM module is schematically shown.

Fig. 4.20 Trigger efficiency curve as a function of electron energy is shown. This is made from Fig. 4.21 by convoluting energy resolution.

Fig. 4.21 Trigger efficiency curve as a function of electron visible energy is shown. Physics analysis is based on the visible energy. This efficiency was measured by two level trigger calibration. Trigger thresholds were set at two levels: one is the same as normal data taking, and the other is a sufficiently low threshold to guarantee full efficiency around the normal threshold. All data taken with a low threshold were analyzed and visible energies were reconstructed. Then, a trigger flag from the normal threshold was checked and the trigger efficiency as a function of visible energy was obtained.

Fig. 4.22 Trigger threshold (solid) and analysis threshold (dots) are chronologically shown. Trigger threshold is defined by the energy where the trigger efficiency becomes 50%.

Fig. 4.23 Decay chains of U-Ra and Th series are shown with half lives and decay modes.

Fig. 4.24 Flow lines of water purification system (solid) and radon-free air system (dots) are schematically shown. Underlined instruments were newly installed for Kamiokande-3.

Fig. 4.25 Event rate at a particular reduction step (effectively 6 MeV threshold and 1550 tons of effective volume), where the background is dominated by radon is plotted as a function of data taking time. We installed cooled charcoal in the beginning of December 1990. Solid line is decay curve with ^{222}Rn half life (3.824 days). Measured radon concentration in the detector water is also shown. Data after the end of December 1990 is used for the solar neutrino analysis.

Fig. 4.26 Schematic of the radon measurement system. Radon measurement system consists of two parts: water collection system (upper drawing) and radon concentrating system (lower drawing).

Fig. 4.27 Schematic of Lucas (ZnS paint) counter is shown. Radon-rich gas is inserted through Swage lock. 2-inch PMT is attached on the Lucite window.

Fig. 4.28   Typical pulse height distribution of radon measurement with Lucas counter (ADC counts vs. number of events) is shown.

Fig. 4.29   Count rate of radon measurement is shown as a function of data taking time. Intrinsic background measurement was done for the period from 0 to 5500 minutes, and the average noise rate was 0.25 counts/minute. Radon gas extracted from 560 milli-liter of mine water (which contains 280 pCi/l of radon contamination) after 200 hours of decay time was inserted into Lucas cell at 5500 min for the calibration of the detection efficiency. At 14200 min, Lucas cell was vacuumed out and radon gas was extracted from the cell. After decaying the daughter atoms, radon gas extracted from 20 liters of tank water after 32 hours of decay time was inserted at 14500 min.

Fig. 4.30   Count rates of the radon measurement soon after radon insertion and after vacuum disposition are shown as a function of time. Solid line is fitted result of the shape by a function expected from half lives of atoms in the decay chain.

Fig. 4.31   Schematic of radon counter using solid state detector is shown. The daughter ions decayed from ^{222}Rn inside the mesh anode are gathered onto PIN photo-diode by 60 to 100 V of bias voltage.

Fig. 4.32   Observed energy spectrum by the SSD radon counter is shown. Decaying nuclei are clearly separated due to its good energy resolution.

Fig. 4.33   SSD radon counter specially constructed for sinking into water is schematically drawn. Micro-porous film prohibits water from entering but allows radon gas to enter.

Table 5.1   Isotopes accompanying beta and/or gamma rays with an energy greater than 7 MeV are listed with their half lives, emitted particles and released energies. The entries are chosen from nuclei whose mass numbers are less than or equal to 16.

Fig. 5.1   Vertex difference between fast and precise reconstruction is shown. Data used are the final sample of solar neutrino analysis in Kam-3.

Fig. 5.2   Opening angle distribution of Cherenkov photons from an incident electron direction obtained from 10 MeV Monte Carlo events is shown. This distribution is used for the direction reconstruction as a likelihood function.

Fig. 5.3   Effective surface area is shown for the 20-inch PMT with and without the light reflector as a function of light direction. Light acceptance has increased due to light reflectors at angles smaller than 55 degrees.

Fig. 5.4   Relation of electron total energy and effective number of hit PMTs is plotted. Monte Carlo events were generated in the whole volume and only

the events reconstructed in the fiducial volume and clearing the gamma cut were used for obtaining the relation.

Fig. 5.5   PMTs used for muon track reconstruction are schematically illustrated.

Fig. 5.6   Monte Carlo simulation of electron tracks in water is shown for electrons with 10 MeV of kinetic energy. Twenty electron tracks are overlaid in the figure.

Fig. 5.7   Pulse-height distribution of one photo-electron signal with Kam-3 electronics is shown. This distribution is obtained from low hit Ni+Cf calibration data which statistically guarantees only one photo-electron in the hit signal. This distribution is used for the detector simulation.

Fig. 5.8   Vertex spread of Ni(n,γ)Ni' calibration data taken at the center of the detector is shown as a function of energy, together with that for Monte Carlo events. Vertex spread is defined by the radius where 68% of events are observed inside the sphere. The contribution of Cf background is statistically subtracted from the data. The vertex distribution of Monte Carlo events is well reproducing that of real data.

Fig. 5.9   Vertex distribution of Ni+Cf calibration data taken at the edge of the fiducial volume (x, y, z)=(0.08m, −0.16m, 4.5m) is compared with the Monte Carlo distribution. The contribution of Cf background is statistically subtracted. The distribution is well reproduced by the Monte Carlo simulation.

Fig. 5.10   Pulse-height distributions of muons in inner-detector and anti-counter are shown. Muons are selected by inner-total-p.e. > 10000 for anti-counter or anti-total-p.e. > 400 for inner detector. Time difference cut $\Delta T > 20$ μsec is also applied to reject ringing noise.

Fig. 5.11   Vertex distribution of the fast reconstruction step is shown. Region denoted by "cut" (1.5 m on average from the edge of the fiducial volume) is rejected before making the precise vertex reconstruction.

Fig. 5.12   The "goodness" distribution of the fast reconstruction is compared between normal data and noisy data. The noise cut criteria is set at "goodness" ≥ 0.4.

Fig. 5.13   Normal data and noisy data are compared for the noise cut parameters N_{hit}/N_{dsc} and N_{neg}/N_{dsc}.

Fig. 5.14   Vertex distribution of the precise reconstruction step is shown for the events above 6 MeV.

Fig. 5.15   The definition of x-y-z axes are shown. Z-axis penetrates the center of the cylindrical tank vertically toward upper side. X-y plane is off-set by 60 cm below the center of the inner-detector. But, the fiducial volume in Kam-3 is

set in a symmetric region ($-3.37m \leq z \leq 4.57m$). X-axis is $30.42°$ rotated to south direction from east direction.

Fig. 5.16 The energy spectra for full volume (open circles), fiducial volume (black diamonds), after spallation cut (open diamonds) and final sample (black circles) data are shown. Expected spectrum from the SSM [ref 1-5] is also shown (solid line).

Fig. 5.17 Time difference distribution from muons ($Q_{eff} \geq 20000$ p.e.) is shown for the events above 7 MeV. Short (several tens milli-second), middle (a few second) and long (about ten second) decay components are seen.

Fig. 5.18 Spallation cut criteria is defined as a function of preceding muon pulse height and time difference from the muon. All low energy events in region denoted by "1" are rejected, and events in region "2" are rejected when the distance from the vertex to the muon track is less than 3 meters. Events in region "3" are rejected when the distance is less than 2 meters.

Fig. 5.19 The distance of the vertex from the muon track is shown for the events before the spallation cut with the conditions of $Q_{eff} \geq 20000$ p.e., $E_e \geq 9$ MeV and $\Delta t < 1$ sec. Solid histogram is the observed distribution and dashed histogram is the contribution of random coincidence events which is obtained from random combinations of muons and low energy events (time difference is neglected).

Fig. 5.20 Timing and spatial correlation of stopping muons (which do not have a decay electron) and low energy events are shown. Solid line in timing distribution is fitted result of the histogram decay curve with ^{16}N decay (τ=10.29sec) and flat background. Dashed line in vertex distance distribution is the contribution of random coincidence events whose normalization is determined by the flat component of the decay curve fit.

Fig. 5.21 The vertex distribution after the spallation cut is shown. Event rate at the edge of the fiducial volume is larger than that at the center of the volume.

Fig. 5.22 The directional distribution of the events after the spallation cut with respect to the direction of the nearest wall is shown for the events of which the vertex is located within 1 meter from the edge of the fiducial volume (upper histogram) and for the events in the remaining region (lower histogram). Inner direction is defined as $\cos\theta = -1$. The excess toward the inner-direction is clearly seen for the events close to the wall.

Fig. 5.23 Energy spectra after spallation cut are shown for every interval of 100 days of data taking. Only soft component below 8 MeV which is estimated to be originated by radon is decreasing.

Fig. 5.24 Time differences from muons ($10000 \leq Q_{eff} < 20000$, $20000 \leq Q_{eff} < 40000$, $40000 \leq Q_{eff}$) are shown for the data before and after the spallation cut. Contributions of spallation products are estimated from the decay components (time-correlating components) in the figures.

Fig. 5.25 Energy spectra of anti-neutrinos from ^{239}Pu, ^{241}Pu, ^{238}U and ^{235}U [ref 5-9] are shown.

Fig. 5.26 Anti-neutrino spectrum from reactors is shown for Kamioka site.

Fig. 5.27 Expected energy spectrum of reactor neutrino events in Kamiokande is shown.

Fig. 6.1 Angular distribution of solar neutrino events (normalized at each energy) is shown for the visible energy of recoil electron; 7, 10 and 15 MeV. These distributions are used for likelihood function of solar neutrino counting. θ_{sun} is the opening angle from the direction to the sun.

Fig. 6.2 (a) Angular distributions of final sample are shown for 200.3 days of 7.5 MeV threshold data and 314.2 days of 7.0 MeV threshold data. Super-imposed solid histograms are expected solar neutrino distributions over the flat background and dashed histograms are the best fits of the excess toward the sun with expected angular distribution scaled by 0.543 (=data/SSM) and 0.591, respectively.

(b) Same as (a) but for total 514.5 days of Kam-3 data and total 1557 days of Kamiokande data. Best fit values are 0.574 and 0.514, respectively.

Fig. 6.3 Distribution of relative likelihood as a function of "solar ν events" / "all events" for 1557 days of total combined data.

Fig. 6.4 Energy spectrum of solar neutrino events from 1557 days of total combined data is shown. Data bins above 14 MeV are combined.

Fig. 6.5 Energy spectrum of solar neutrino events from 1557 days of total combined data with respect to the expected event rate from the SSM [ref 1-5] is shown. Dashed lines are expected from SSM (ratio = 1) and best fit of all combined data (ratio = 0.514).

Fig. 6.6 ^{37}Ar production rate as a function of sun-spot numbers are shown. Solid line is the best fit line of the correlation as seen in (eq 6-9), and dashed one is the shifted line of the best fit one to obtain the same average value derived by Davis et al.

Fig. 6.7 Sun-spot numbers as a function of time (year) [ref 6-4] are plotted. Those values are averaged for every one month duration.

Fig. 6.8 Solar neutrino flux with respect to the SSM prediction is plotted for every 200 days of data. Sunspot numbers for the periods are inversely super-imposed in the figure.

Fig. 6.9　Contour plots of χ^2 distribution in α-β plane are shown for different and common threshold of 7 data points. 68% and 90% contour lines are obtained by $\chi^2 = \chi^2_{min} + 2.28$ (68%) and 4.605 (90%), respectively. One sigma error and 90% C.L. region for a parameter are obtained at $\chi^2 = \chi^2_{min} + 1$ (1 sigma), 2.69 (90% C.L.).

Fig. 6.10　Interesting regions for solar neutrino observation "S" and for anti-neutrino search "B" are illustrated. Region "A" ($\cos\theta_{sun} < 0.8$) was used for the anti-neutrino search.

Fig. 6.11　Observed energy spectrum with $\cos\theta_{sun} < 0.8$ for 593.7 days of Kam-2 gain×2 data is shown. This spectrum was used for deriving a flux limit of solar anti-neutrinos.

Fig. 6.12　Spectrum independent $\bar{\nu}_e$ flux limits are plotted. Circle plots show 90% C.L. upper limit of $\bar{\nu}_e$ flux in unit of (/cm^2/sec). ^{8}B solar neutrino spectrum expected by the SSM [ref 1-5] and calculated reactor $\bar{\nu}_e$ spectrum are superimposed with the different unit of (/cm^2/sec/MeV). These limits are obtained from Kam-2 gain×2 data.

Fig. 6.13　$\bar{\nu}_e$ flux limit as a ratio with ^{8}B solar neutrino flux expected by the SSM is plotted in unit of (/MeV). Attention is needed, because the unit of spectrum independent flux limit is (/cm^2/sec) but the unit of ^{8}B solar neutrino flux is (/cm^2/sec/MeV). We assumed that the $\bar{\nu}_e$ spectrum is distributed over one MeV width, or one does not require a fine binding less than one MeV width. With such an assumption, these spectrum independent flux limits can be considered as normal ratios.

Fig. 7.1　90% C.L. allowed region in δm^2-$\sin^2 2\theta$ plane by Kamiokande result on average flux (energy spectrum is not used) is shown. Two flavor neutrino oscillation is taken into account. But, earth effect is not considered.

Fig. 7.2　90% C.L. allowed region in δm^2-$\sin^2 2\theta$ plane by Kamiokande result considering energy spectrum is shown.

Fig. 7.3　90% C.L. allowed region in δm^2-$\sin^2 2\theta$ plane by Chlorine result from 1970 (run 18) to 1990 (run 114) is shown. Time variation of the flux is not considered.

Fig. 7.4　90% C.L. allowed region in δm^2-$\sin^2 2\theta$ plane by Gallium result is shown. All available SAGE and GALLEX results are used (i.e. SAGE30 1990, SAGE60 1991, GALLEX-I June 1991 to April 1992 and GALLEX-II August 1992 to April 1993).

Fig. 7.5　90% C.L. allowed region for all three types of experiments is shown. Shaded region appears by considering the earth effect.

Fig. 7.6　Expected energy spectra at Kamiokande are shown for the typical parameters in the allowed region of Fig. 7.5. Parameters $(\delta m^2, \sin^2 2\theta) = (10^{-5.2} eV^2, 10^{-2.2})$ for non-adiabatic solution and $(10^{-5.4} eV^2, 10^{-0.2})$ for quasi-vacuum solution are used. Plots are observed energy spectra and solid histograms are the expected energy spectra. In this calculation, earth effect was also taken into account.

Fig. 7.7　Density distribution in the earth [ref 7-2] used for the calculation of earth effect is shown.

Fig. 7.8　90% C.L. allowed region in δm^2-$\sin^2 2\theta$ plane by Kamiokande result (without energy spectrum information) is shown. In this region vacuum oscillations play an important role.

Fig. 7.9　90% C.L. allowed region by Kamiokande result considering energy spectrum information is shown.

Fig. 7.10　90% C.L. allowed region by Chlorine experiment is shown for just-so oscillation solution.

Fig. 7.11　90% C.L. allowed region by gallium experiments is shown. Small regions around $(\delta m^2, \sin^2 2\theta) = (10^{-11.1} eV^2, 1)$ and $(10^{-10.9} eV^2, 0.5)$ are not allowed in the figure.

Fig. 7.12　Electron and neutron number density in the sun [ref 1-5] used for the calculation of neutrino propagation. Horizontal axis is radius as a ratio to the solar radius. Vertical axis is the density in units of mol/cm^3 $(=6.022\times10^{23}/cm^3)$.

Fig. 7.13　Akhmedov type magnetic profile [ref 7-6] in the sun is shown. Parameters for magnetic strength in the convection zone B_0 and that in radiation zone B_1 are given by 20 kGauss and 1 MGauss.

Fig. 7.14　Distribution of solar neutrino production points for each neutrino emission reaction are shown. These distributions are considered in the neutrino oscillation and resonant spin flavor precession calculations.

Fig. 7.15　Neutrino propagation of Majorana neutrinos in the hybrid model is shown for several magnetic profile and parameter sets:
constant magnetic filed $(B, \delta m^2, \sin^2 2\theta) = (20\ kG, 3\times10^{-7}\ eV^2, 0.1)$, $(20\ kG, 7\times10^{-8} eV^2, 0.3)$,
Akhmedov type magnetic field $(B_0, B_1, \delta m^2, \sin^2 2\theta) = (20\ kG, 20\ kG, 7\times10^{-8}\ eV^2, 0.3)$,
without magnetic filed $(\delta m^2, \sin^2 2\theta) = (7\times10^{-8} eV^2, 0.3)$,
Akhmedov type magnetic field $(B_0, B_1, \delta m^2, \sin^2 2\theta) = (3\ MG, 20\ kG, 10^{-5}\ eV^2, 0.2)$, and $(1\ MG, 50\ kG, 4\times10^{-7}\ eV^2, 1)$.

Neutrino energy is 10 MeV, and transition magnetic moment is fixed at $10^{-11} \mu_B$.

Fig. 7.16 90% C.L. allowed regions in δm^2-$\sin^2 2\theta$ plane by Chlorine experiment are shown for various configuration of magnetic field. Both neutrino oscillation and spin flavor precession (of Majorana neutrinos) are now taking place, but the time variation of the experiment is not considered yet. Magnetic profile in the sun is an Akhmedov type profile with B_1 = 1M, 3M, 300k, 100k, 0 Gauss and B_0 = 1k, 2k, 5k, 10k, 20k, 25k, 30k, 35k, 40k, 45k, 50k, 60 kGauss for each B_1 value, flat magnetic field only in the convection zone (r/R_{sun} >0.65) with 12 types of B_0 values, and flat magnetic field in the sun also with 12 types of B_0 values. Transition magnetic moment of neutrinos is fixed at $10^{-11} \mu_B$. Horizontal and vertical axes are in units of $\log(\sin^2 2\theta)$ and $\log(\delta m^2 \text{[eV}^2\text{]})$.

Fig. 7.17 Same plot as Fig. 7.16 but allowed by gallium experiments.

Fig. 7.18 Same plot as Fig. 7.16 but allowed by Kamiokande result considering energy spectrum information. View port in δm^2-$\sin^2 2\theta$ plane is now expanded.

Fig. 7.19 Parameter sets of (δm^2, $\sin^2 2\theta$) where time variation of the solar neutrino flux in Chlorine experiment can be explained at 90% C.L. in α-β parameter space (data/SSM = $\alpha N_{ss} + \beta$) are plotted. Magnetic field in the convection zone (B_0) is ranging from 1 kG to 60 kGauss as a free parameter, and 7 types of magnetic profiles are characterized by magnetic field in the radiation zone (B_1 = 1M, 3M, 300k, 100k and 0 Gauss for Akhmedov type profile) and the shape of the magnetic field (Akhmedov type, flat only in the convection zone, or flat in the sun). Magnetic (transition) moment of neutrinos is fixed at $10^{-11} \mu_B$.

Fig. 7.20 Same plot as Fig. 7.19 but both the time variation in Chlorine experiment and neutrino deficit in gallium experiments (data/SSM = 0.55 ± 0.11 at the solar maximum period) can be explained.

Fig. 7.21 Expected flux variation of Chlorine, Gallium and Kamioka (9.3, 7.5 and 7.0 MeV thresholds) experiments in terms of magnetic amplitude in the convection zone (B_0) are shown. Parameter sets of (B_1, δm^2, $\sin^2 2\theta$) are chosen from typical values obtained in Fig. 7.20: (1 MG, $10^{-6.85}$ eV^2, $10^{-2.2}$), (3 MG, $10^{-6.85}$ eV^2, $10^{-2.6}$), (300 kG, $10^{-8.45}$ eV^2, 1), (flat in the convection zone, $10^{-7.55}$ eV^2, 0.01), (flat in the convection zone, $10^{-8.05}$ eV^2, 1) and (flat, $10^{-7.45}$ eV^2, $10^{-2.4}$). Obtained B_{min} (amplitude at solar minimum, $N_{ss} \sim 20$) and B_{max} (at solar maximum, $N_{ss} \sim 150$) are also shown in the figure.

Fig. 7.22 Same plot as Fig. 7.19 but the time variation in Chlorine and Kamiokande experiments are satisfied at 90% C.L.

Fig. 7.23 Same plot as Fig. 7.21 but parameter sets are chosen from the typical values obtained in Fig. 7.22: (1 MG, $10^{-6.95}$ eV^2, 0.1), (3 MG, $10^{-6.95}$ eV^2, 0.1), (0 G, $10^{-7.65}$ eV^2, $10^{-0.3}$), (flat in the convection zone, $10^{-7.65}$ eV^2, $10^{-0.3}$), (flat in the convection zone, $10^{-8.35}$ eV^2, $10^{-2.5}$), (flat, $10^{-7.95}$ eV^2, $10^{-1.2}$).

Fig. 7.24 Same plot as Fig. 7.19 but all experiments are satisfied. This is a hybrid solution of the solar neutrino problem, which can explain both the neutrino deficits and their time variations.

Fig. 7.25 Same plot as Fig. 7.21 but parameter sets chosen from the typical values obtained in Fig. 7.24: (300 kG, $10^{-8.65}$ eV^2, 1) and (flat in the convection zone, $10^{-7.95}$ eV^2, $10^{-2.3}$)

Fig. 7.26 Hybrid solution obtained by H.Nunokawa [ref 1-32] is shown.

Fig. 7.27 Neutrino propagation is traced from the center of the sun to the surface of the sun and moreover to the earth for a hybrid solution parameter set, (δm^2, $\sin^2 2\theta$) = (2.2×10^{-9} eV^2, 1) with flat magnetic field (50 kG, 20 kG and 10 kG) in the convection zone. Large amounts of $\bar{\nu}_e$ are produced via the processes of resonant spin flavor precession (ν_e to $\bar{\nu}_\mu$) and neutrino oscillation in vacuum ($\bar{\nu}_\mu$ to $\bar{\nu}_e$). Neutrino energies are set at 10 MeV, and transition moment of neutrino is fixed at $10^{-11} \mu_B$.

Fig. 7.28 Expected rates of solar $\bar{\nu}_e$ events in Kamiokande final sample above 13 MeV for various magnetic profiles are shown. Contour lines are drawn at 0.01, 0.02, 0.05, 0.1, 0.2, 0.5 and 1 events/day. Change of magnetic amplitude in the convection zone is reflected in $\bar{\nu}_e$ event rate for the parameter region of $\delta m^2 < 10^{-6}$ eV^2, $\sin^2 2\theta > 0.01$. Change of magnetic amplitude in the radiation zone influences the $\bar{\nu}_e$ event rate for the parameter region of 10^{-6} eV^2 $< \delta m^2 < 10^{-4}$ eV^2, $10^{-1.5} < \sin^2 2\theta < 10^{-0.5}$.

Fig. 7.29 Neutrino propagation is traced from the center of the sun to the surface of the sun and moreover to the earth for a parameter set for which $\bar{\nu}_e$ event rate is influenced by the magnetic amplitude in the radiation zone, (δm^2, $\sin^2 2\theta$) = ($10^{-5.8}$ eV^2, $10^{-0.7}$) with Akhmedov type magnetic profile (3 MG, 1 MG and 300 kG) in the radiation zone. Magnetic strength in the convection zone was set at 0G. Neutrino energies are set at 10 MeV, and transition moment of neutrino is fixed at $10^{-11} \mu_B$. In the figures only the probability to appear as $\bar{\nu}_e$ is scaled by a factor of 10.

Fig. 7.30 Expected energy spectrum of $\bar{\nu}_e$ events is compared with the observed energy spectrum in final sample (Kam-2 gain$\times$2, $\cos\theta_{sun} < 0.8$).

Fig. 7.31 Excluded regions of Hybrid parameters for Majorana neutrinos from $\bar{\nu}_e$ flux limit in Kamiokande are shown. Various magnetic profiles are tested, but the excluded region of $\delta m^2 < 10^{-6} eV^2$, $\sin^2 2\theta > 0.01$ is not influenced by the shape of the magnetic field, and is relevant to both of the two flavor hybrid models using Majorana neutrinos. Obtained excluded region covers almost entire hybrid solution suggested in [ref 1-32].

Fig. A.1 Schematic of 20-inch PMT is shown.

Fig. A.2 Quantum efficiency of 20-inch PMT is shown together with the Cherenkov spectrum after traversing 15 m of pure water.

Fig. A.3 Pulse height distortion in terms of photon conversion point (anode uniformity) is shown.

Fig. A.4 Pulse height distortion in terms of magnetic field is shown.

Fig. A.5 Current network around the detector to compensate for the geomagnetic magnetic field is schematically shown.

Fig. A.6 Magnetic shield for 20-inch PMT is shown.

Fig. A.7 Water-proof structure of 20-inch PMT is shown.

Fig. A.8 Holders and support frames for 20-inch PMT is shown.

Fig. B.1 On-line data flow of Kamiokande-2 is schematically shown.

Fig. C.1 Ni converter for the absolute energy calibration using $Ni(n,\gamma)Ni'$ is schematically drawn. Fission neutron from ^{252}Cf is moderated by water in the converter and captured by Ni atoms, then γ-ray emissions arise.

Fig. C.2 A transition scheme of $^{58}Ni(n,\gamma)^{59}Ni$ is shown. Energies of the γ-rays are given at the top and bottom of the level diagram. Relative intensities of the γ-rays are denoted beside the transition arrows in percentage.

Fig. C.3 Ni+Cf calibration spectrum is shown as a function of number of hit PMTs which is one of energy scales.

Fig. C.4 Background spectrum of Ni+Cf calibration measured by Cf source with polyethylene container is shown as a function of number of hit PMTs.

Fig. C.5 $Ni(n,\gamma)Ni'$ spectrum obtained by a subtraction of background contribution (Fig. C.4) from Ni+Cf calibration spectrum (Fig. C.3) is shown. Best fit of Monte Calro spectrum is super-imposed. The width of the distribution is well reproduced by the Monte Carlo spectrum whereas only the peak value is adjusted.

Fig. C.6 Relative $Ni(n,\gamma)Ni'$ energy is shown. The spread of the energy is the ambiguity of the energy measurement in Kamiokande. The spread is inside a $\pm 2.3\%$ region from the central value throughout the full observation time of Kam-2 and Kam-3.

Fig. C.7 Schematic of laser calibration system is drawn. Light emission of N_2-laser is fitted to Cherenkov spectrum by dye. Half of the light is sent to photo-diode to trigger, and rest is sent to MgO diffusing ball through a combination of seven pieces of light attenuator and a 70m length of quartz fiber.

Fig. C.8 Typical measurement of laser calibration is shown with a two dimensional scatter plot of charge and timing values (called a TQ-map). One plot represents one light pulse.

Fig. C.9 Typical two dimensional plot of $\ln\left(L \times Q / S(\theta)\right)$ vs. L of a penetrating muon, where L is the distance from light emission point to hit PMT, Q the pulse height of the hit PMTs and S the effective surface area of the PMT cathode from the direction of θ. The slope of the fitted line (dashes) is the inverse of the light attenuation length.

Fig. C.10 Measured light attenuation length is plotted as a function of data taking time. The attenuation length is now stable around 60m.

Fig. C.11 Light attenuation coefficient as a function of wave length used for the Monte Carlo simulation in Kam-3 is shown. Rayleigh scattering limit is also shown in the figure.

Fig. C.12 Gain variation of PMTs as a function of time is shown by using photo-electrons / track-length of penetrating muons as a gain estimator. The sudden increase ($\times 1.27$) of photo-electrons in December 1990 is due to light reflectors installed for Kam-3. The variation of the gain was stable within 10% throughout the full observation time.

Table D.1 Detector performance of Super-Kamiokande is compared with that of present Kamiokande-3 detector.

The p-p chain

$$p + p \rightarrow D + e^+ + \nu_e \qquad\qquad p + e^- + p \rightarrow D + \nu_e$$

$$99.75\% \qquad\qquad\qquad\qquad 0.25\%$$

$$D + p \rightarrow {}^3He + \gamma$$

$${}^3He + {}^3He \rightarrow {}^4He + 2p \qquad\qquad {}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

$$86\%$$

p-p I

$${}^7Be + e^- \rightarrow {}^7Li + \nu_e \qquad\qquad {}^7Be + p \rightarrow {}^8B + \gamma$$

$${}^7Li + p \rightarrow 2\,{}^4He \qquad\qquad {}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$

$$14\%$$

p-p II

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

$$0.015\%$$

p-p III

Fig. 1.1

The CNO cycle

$$p + {}^{12}C \rightarrow {}^{13}N + \gamma$$

$$\boxed{{}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e}$$

$$p + {}^{13}C \rightarrow {}^{14}N + \gamma$$

$$p + {}^{14}N \rightarrow {}^{15}O + \gamma$$

$$\boxed{{}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e}$$

$$\sim 4 \times 10^{-4}$$

$$p + {}^{15}N \rightarrow {}^{12}C + \alpha \qquad p + {}^{15}N \rightarrow {}^{16}O + \gamma$$

$$p + {}^{16}O \rightarrow {}^{17}F + \gamma$$

$$\boxed{{}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e}$$

$$p + {}^{17}O \rightarrow {}^{14}N + \alpha$$
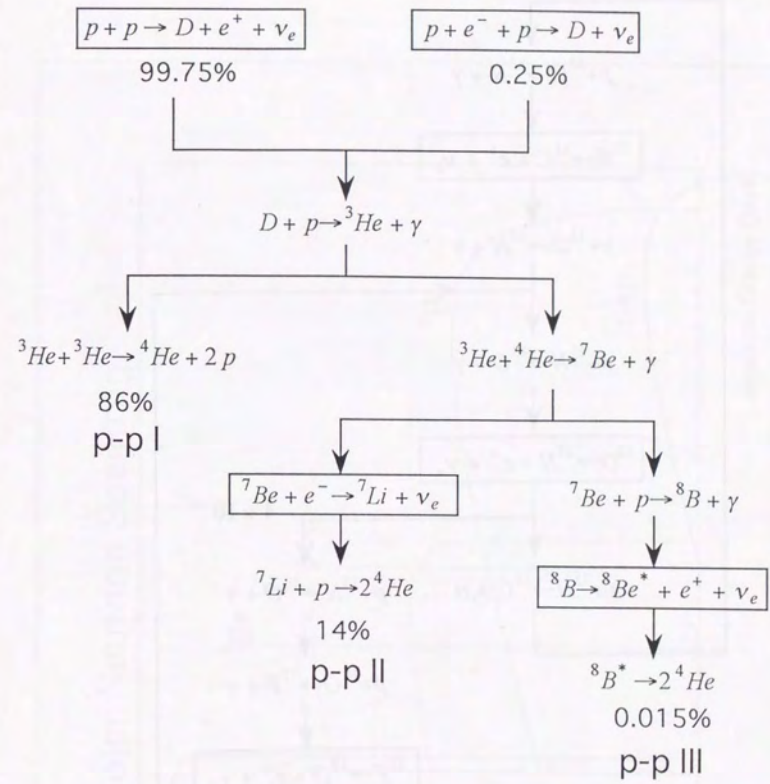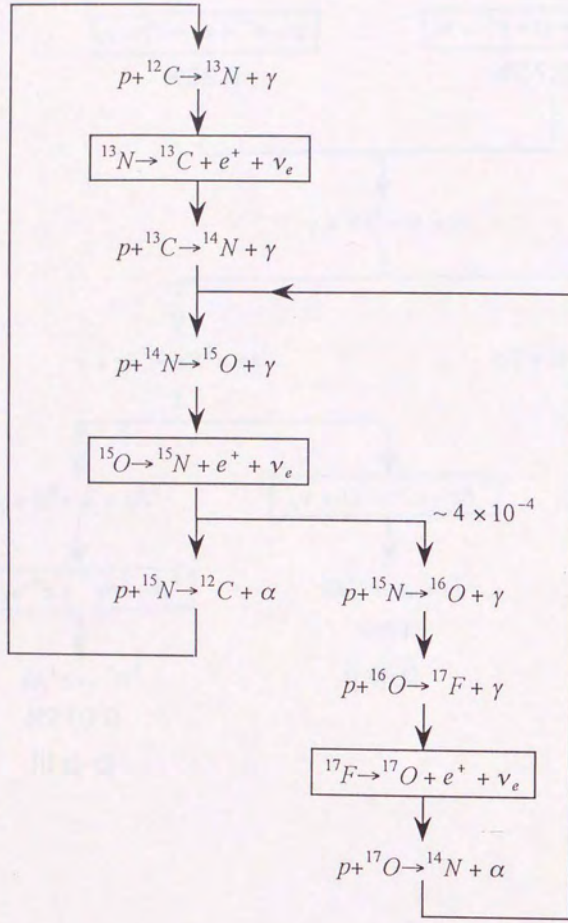
Fig. 1.2
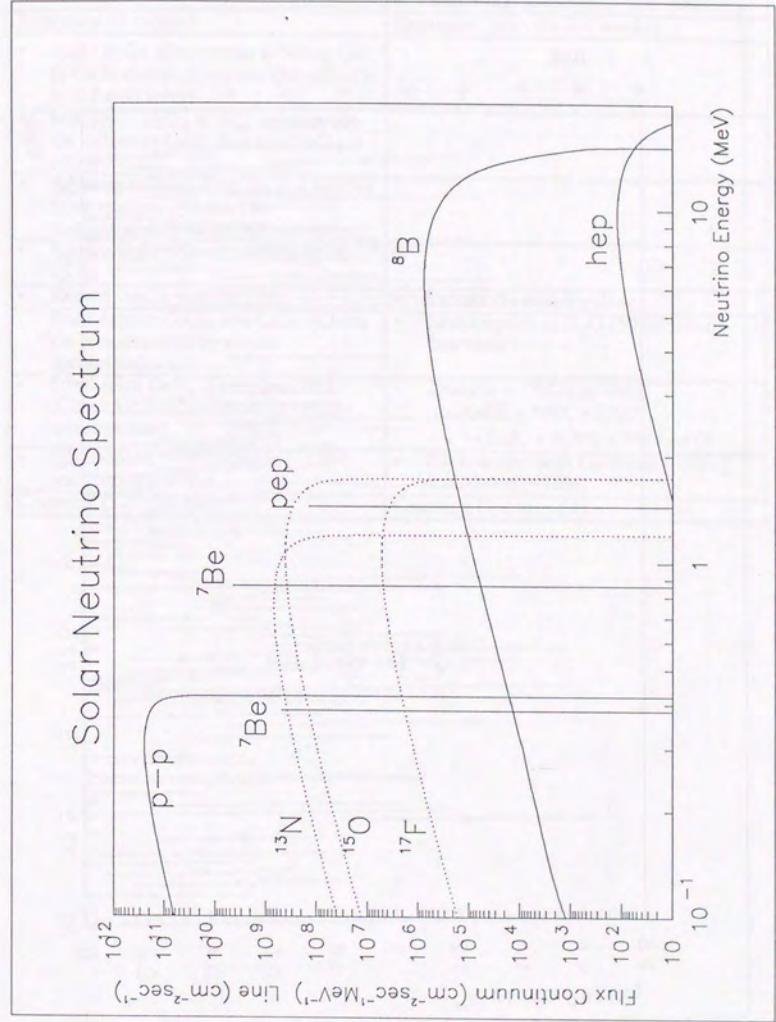
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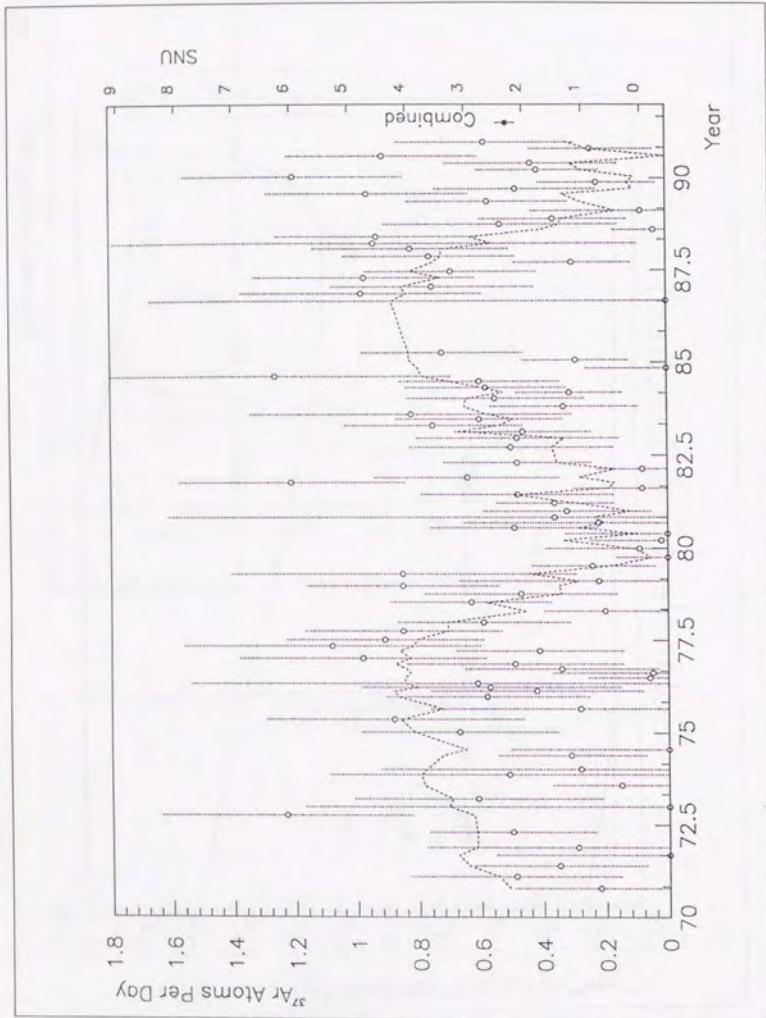
Fig. 1.4

Gallium Extraction Chemistry & Procedures

SAGE (metal target)	GALLEX (aqueous solution)
	• Add 1 mg of carrier (^{70}Ge, ^{72}Ge....)
Exposure (1 month)	Exposure (wait for 3-4 weeks)
• Add Ge-Ga alloy carrier (~500µg Ge) to Ga in chemical reactors (Metallic Ga is in liquid form)	-
• Mix H_2O, H_2O_2 & HCl solution into Ga (Oxidize Ge & dissolve $GeCl_4$ in HCl)	-
• Separate solution from Ga and remove from reactors (Check Ge concentration with atomic absorption)	-
• Reduce H_2O volume and add 12 M HCl	-
• Extract $GeCl_4$ with Ar flow	• Extract Ge with N_2 flow
• Back extract $GeCl_4$ into CCl_4 (Check Ge concentration by atomic absorption)	• Reabsorption in H_2O (50 ml tritium-free water)
• Synthesize GeH_4 (Germane Gas) (Check Ge concentration by volume measurement)	• Transform $GeCl_4$ in GeH_4 $GeCl_4 + KBH_4 + 3H_2O$ $\rightarrow GeH_4 + H_3BO_3 + 3HCl + KCl$
• Fill counters with Germane (~10%) and Xenon (~90%)	• Fill counters with Germane (~30%) and Xenon (~70%)
Counting (3-5 months)	Counting (> 6 months)

Fig. 1.5

Fig. 3.1

Search for Neutrino Oscillation

Fig. 3.2

Fig. 3.3

Excluded Region by Day/Night Study

90%C.L. exclusion
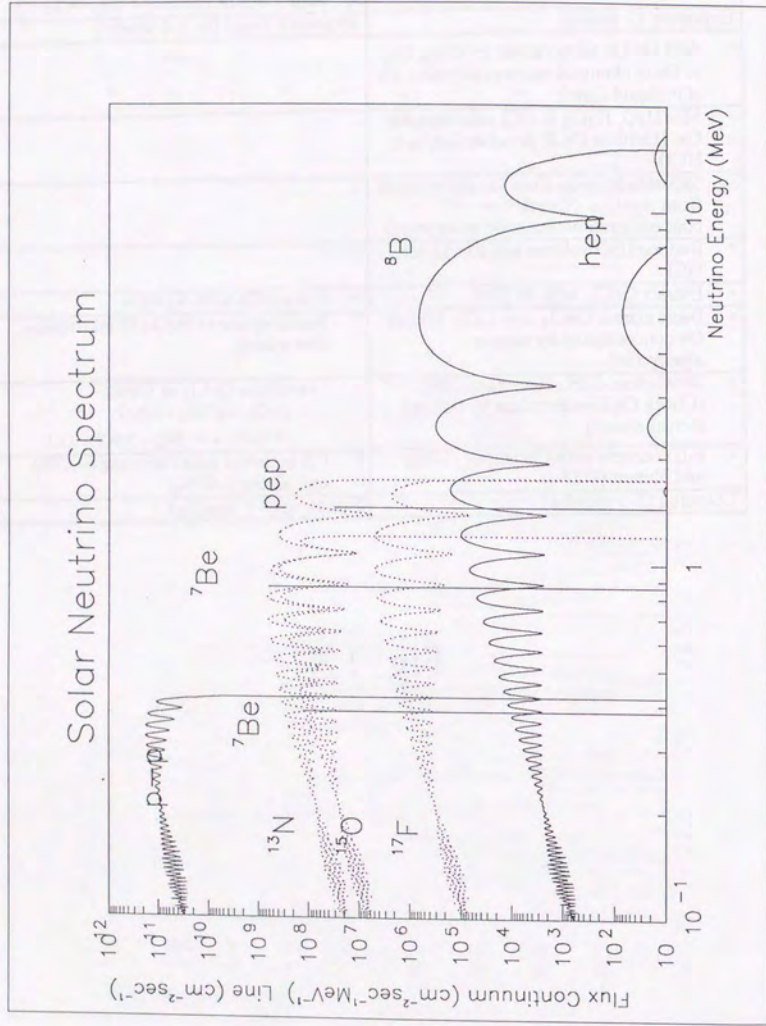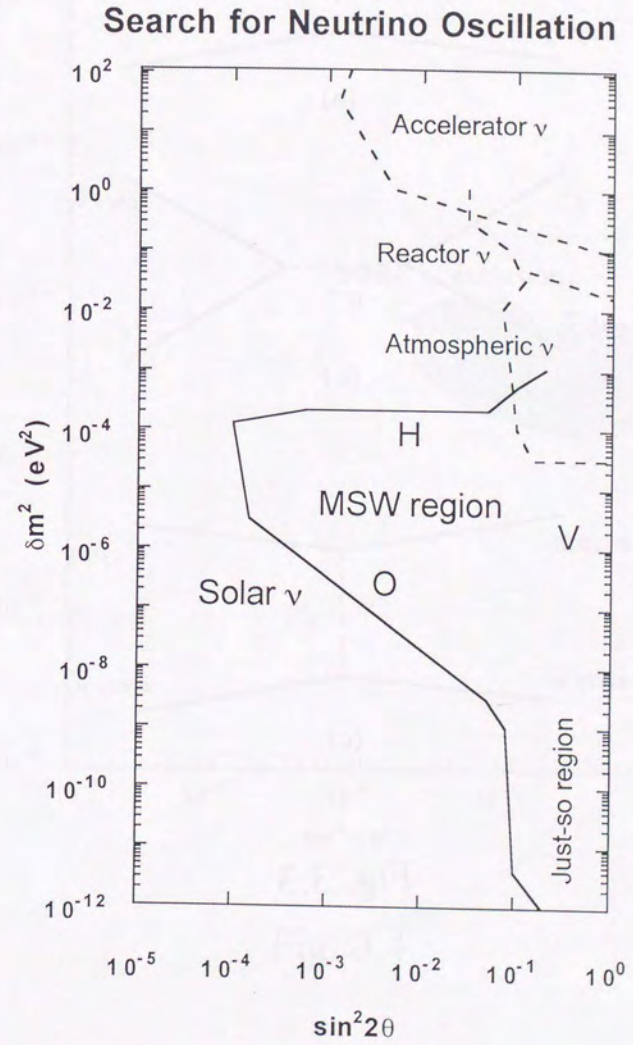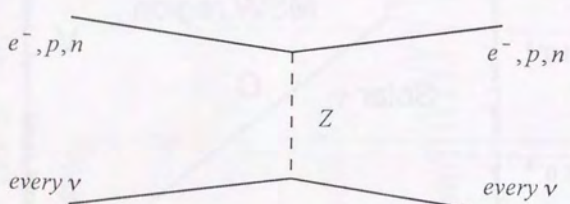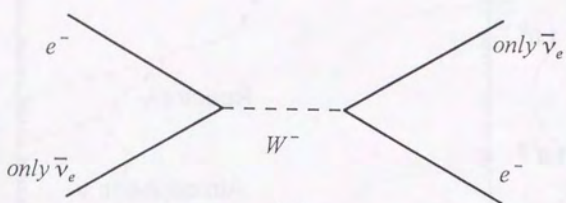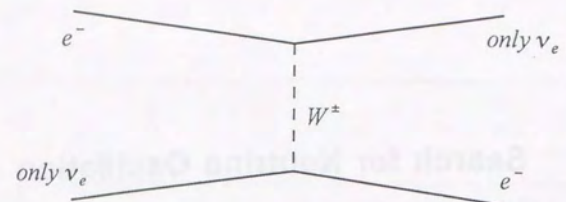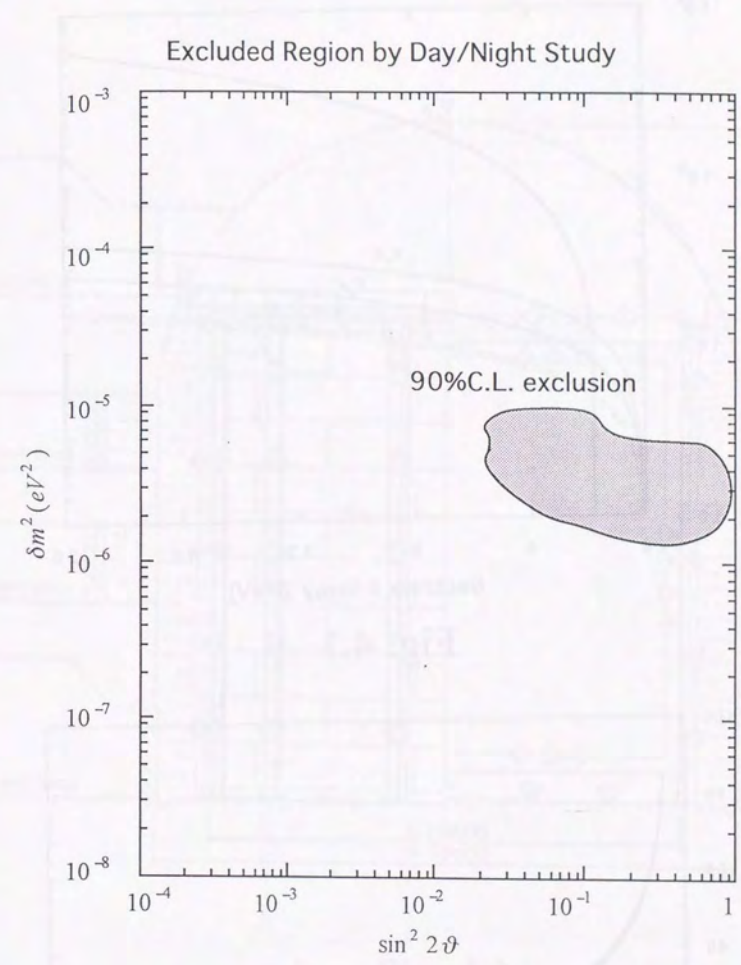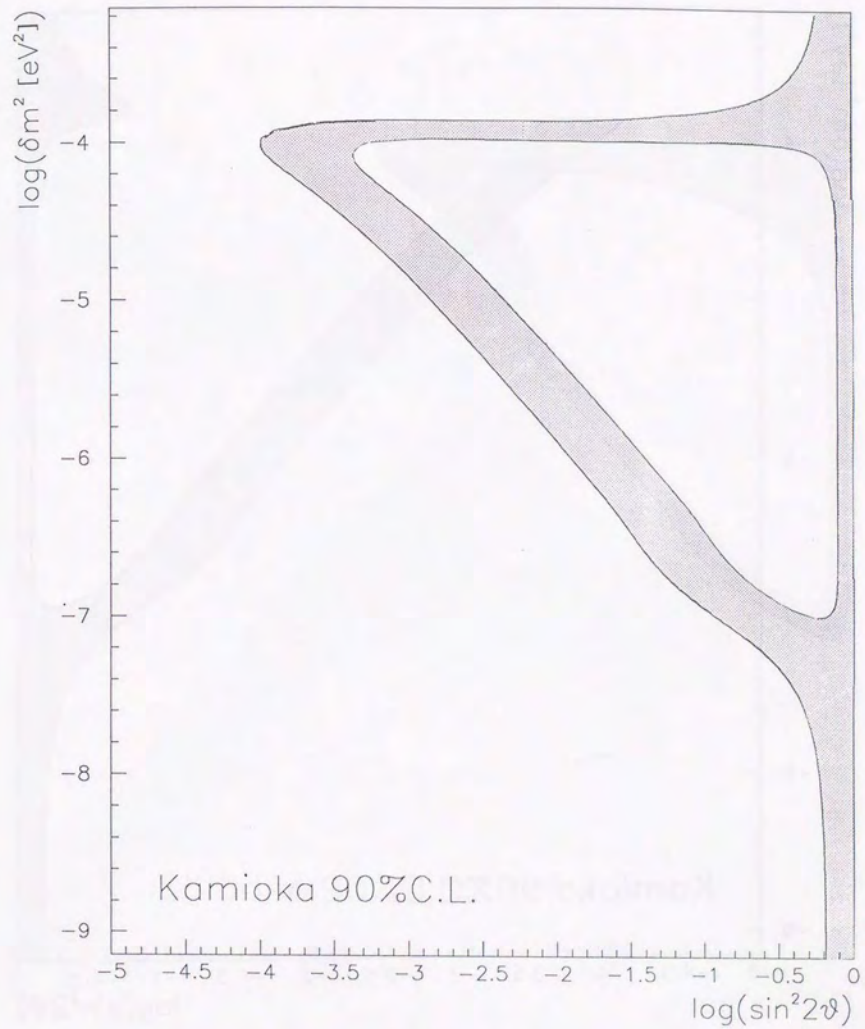
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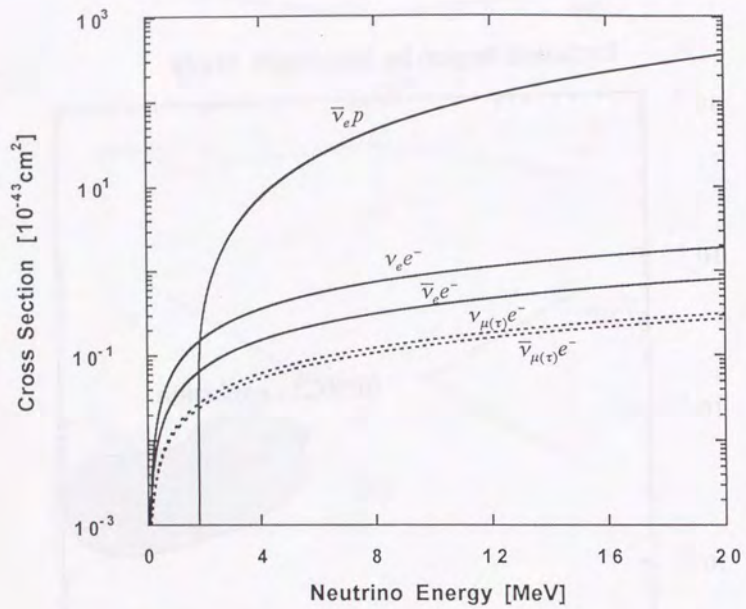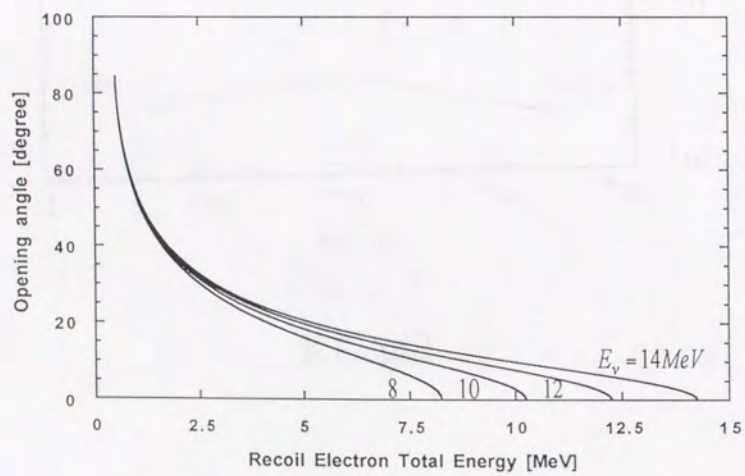
Fig. 4.1

Fig. 4.2
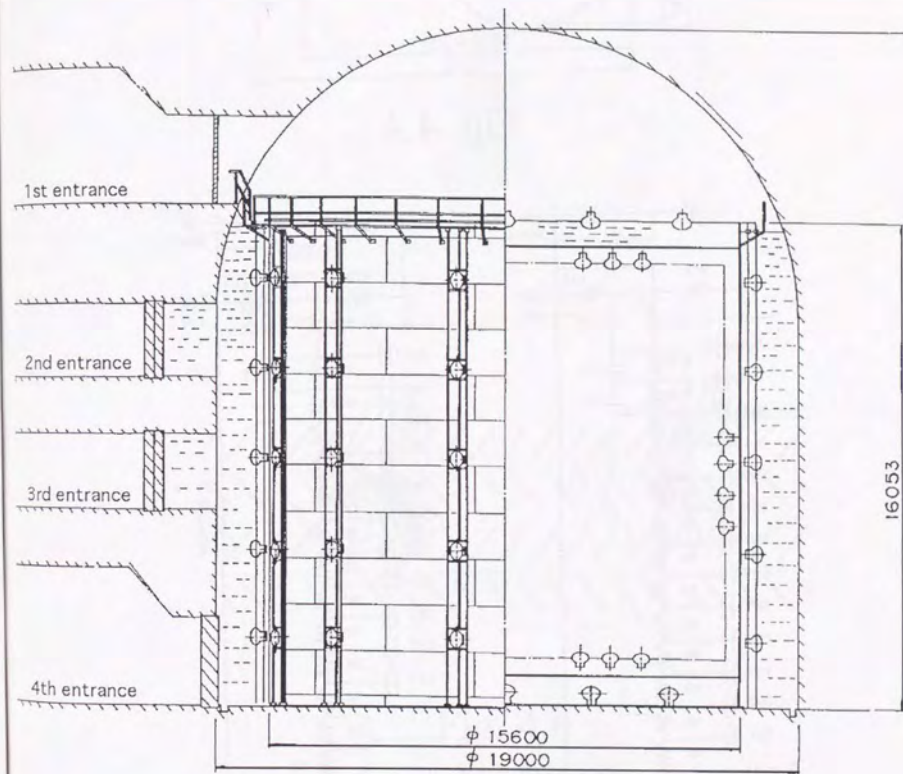
Fig. 4.3

Fig. 4.4
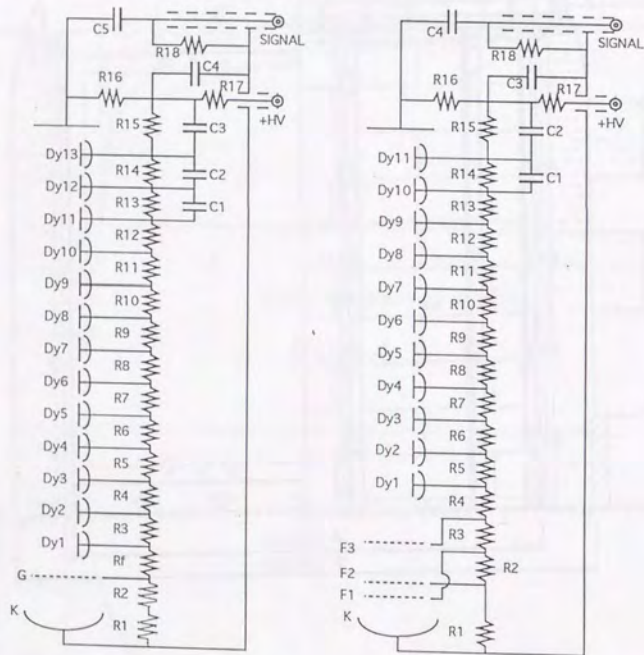
R1,R2 :	1.1M Ω
R3~R15 :	274k Ω
R16 :	200k Ω
R17,R18 :	10k Ω
Rf :	15k Ω
C1~C3 :	0.01 μF
C4,C5 :	0.0047 μF

R1 :	1.3M Ω
R3 :	549k Ω
R4 :	5.49k Ω
R5 :	820k Ω
R2,R6~R15 :	274k Ω
R16 :	200k Ω
R17,R18 :	10k Ω
C1,C2 :	0.01 μF
C3,C4 :	0.0047 μF

Fig. 4.5
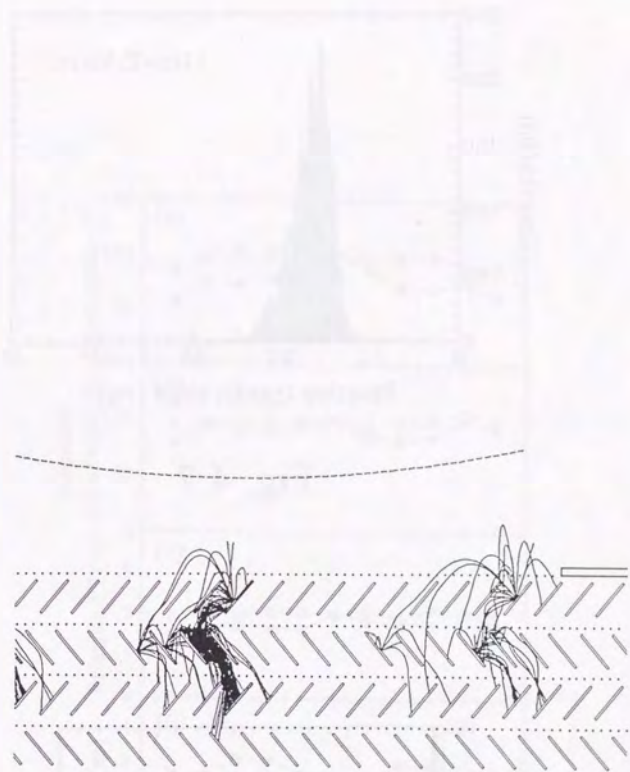
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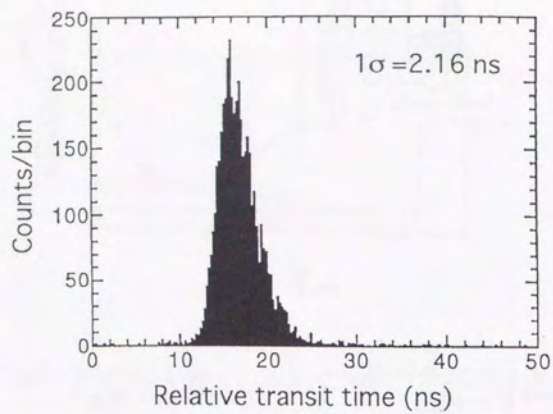
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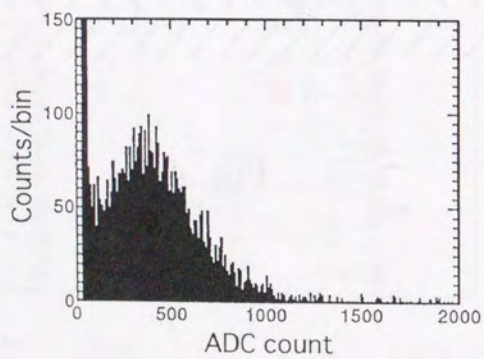
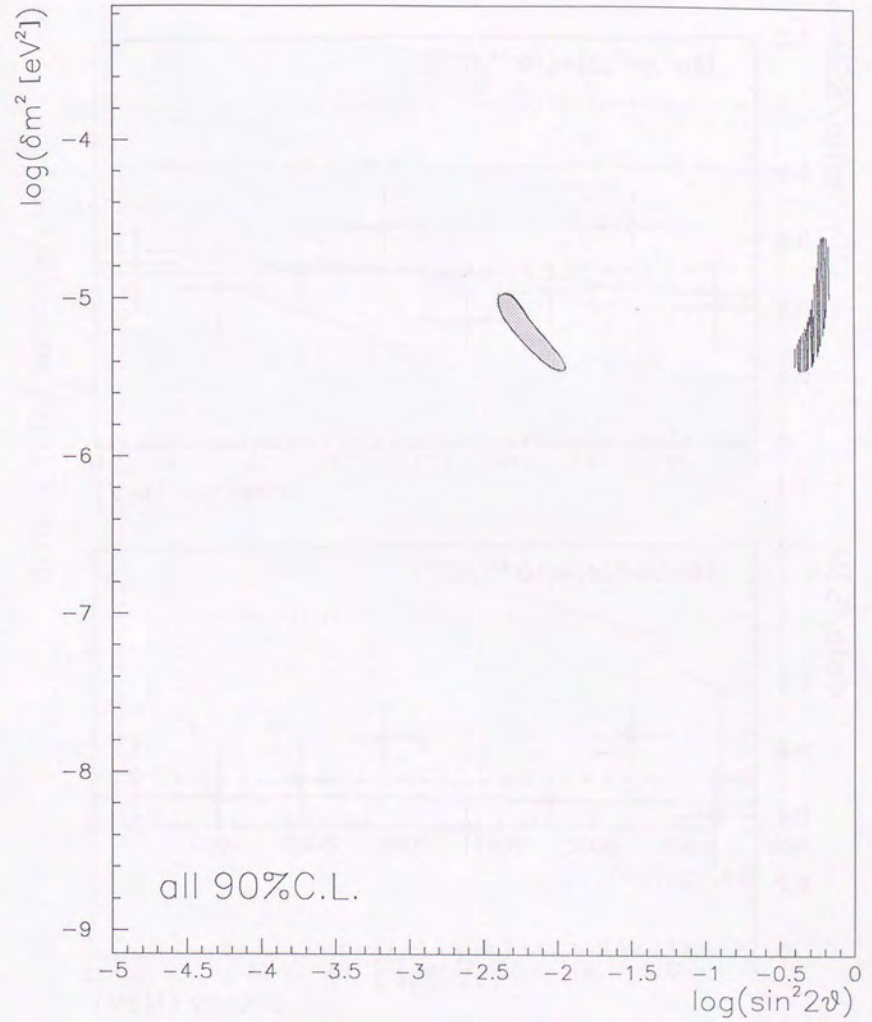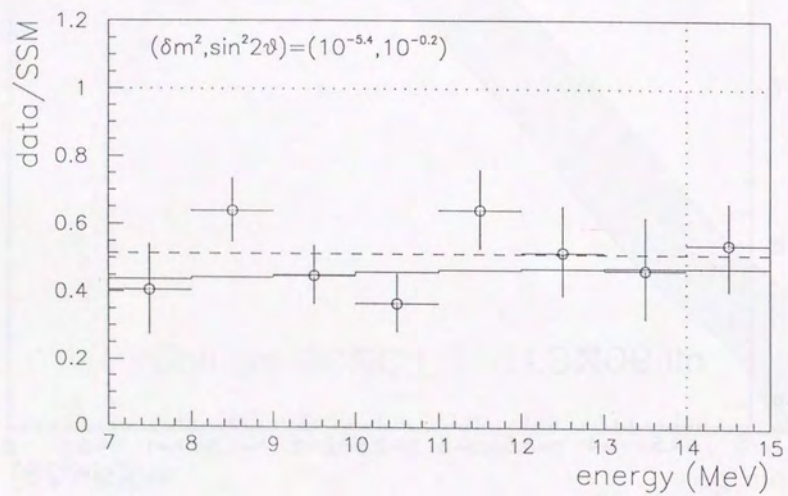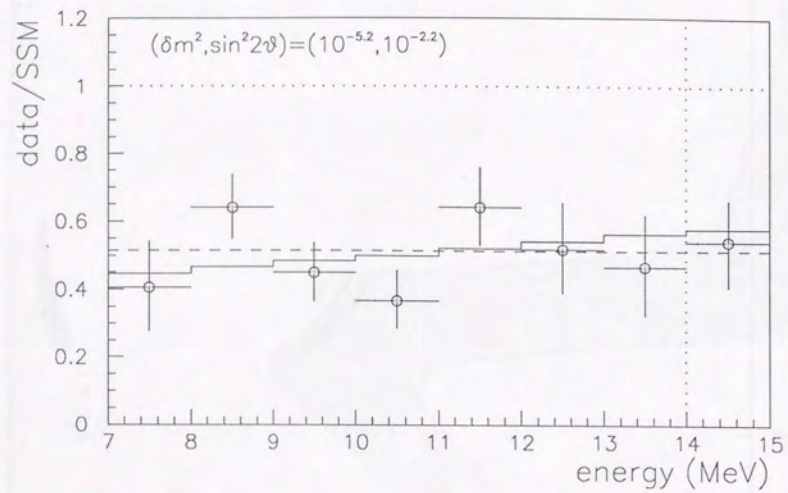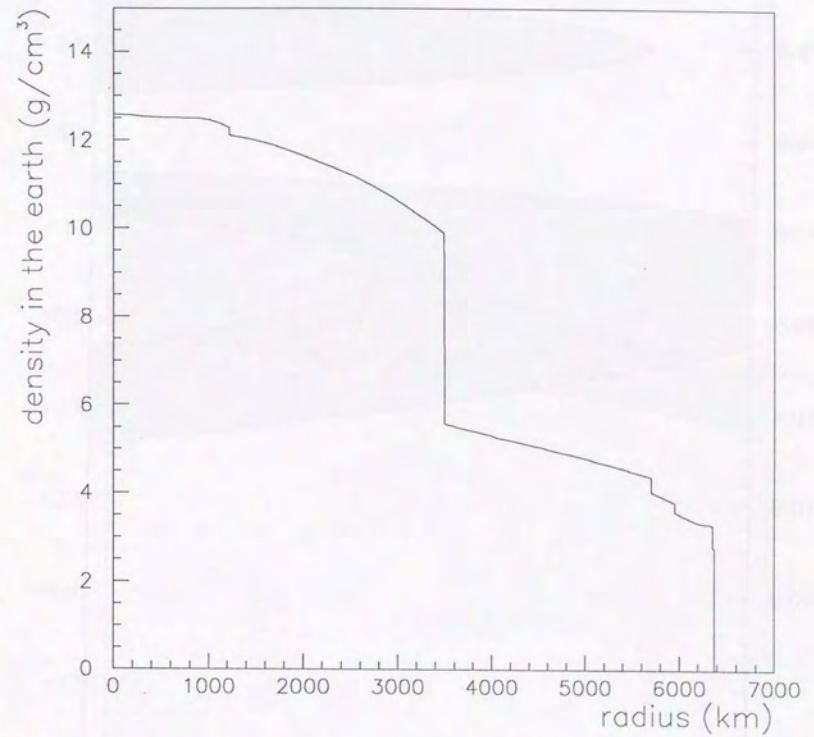
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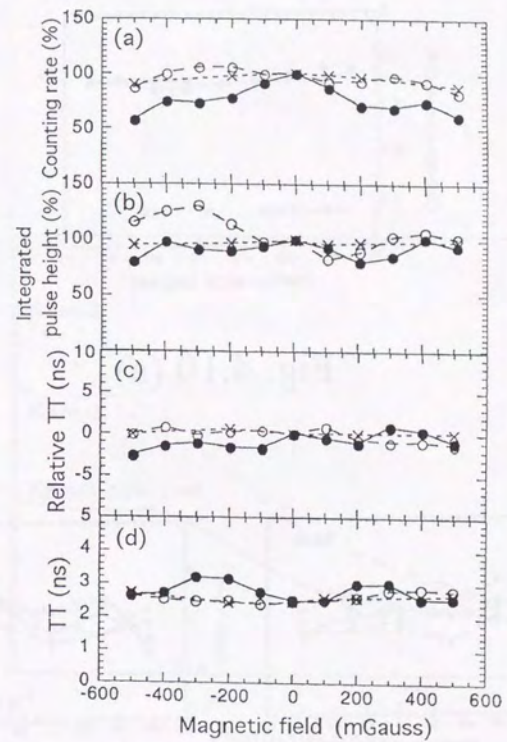
Fig. 4.9

Fig. 4.10 (a)

Fig. 4.10 (b)

Fig. 4.11

SIDE VIEW

FRONT VIEW

60°

106mm
19mm

513mm

619mm

Materials of the Reflector

25 μm PET

dry-ruminate glue

Aluminium
Reflector

300 μm PET

Fig. 4.12

Fig. 4.13

Vertex Resolution (m)

Energy (MeV)

Fig. 4.14

Angular Resolution (degree)

Energy (MeV)

Fig. 4.15

near PMT plane   far PMT plane
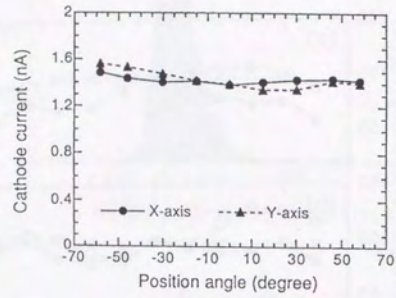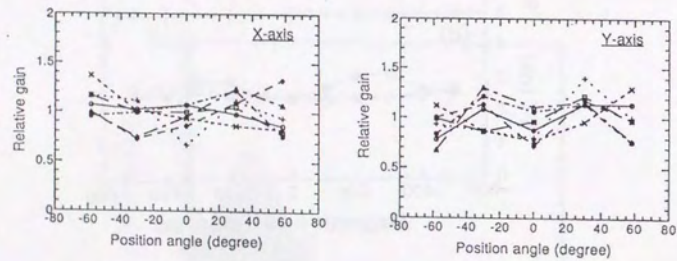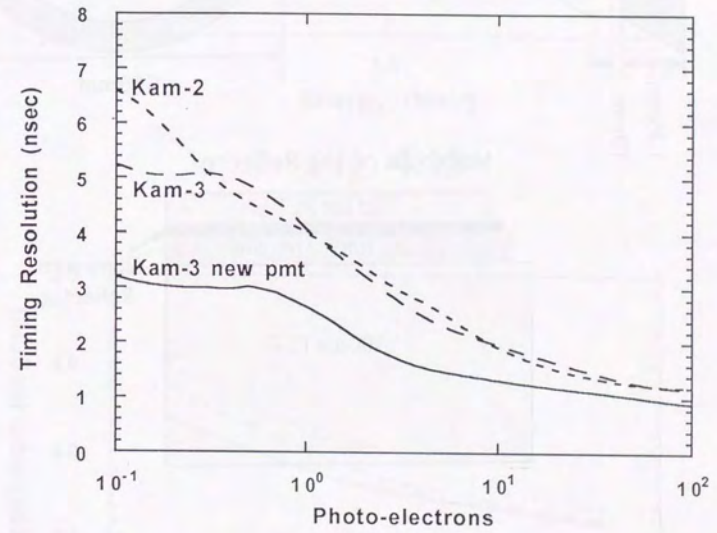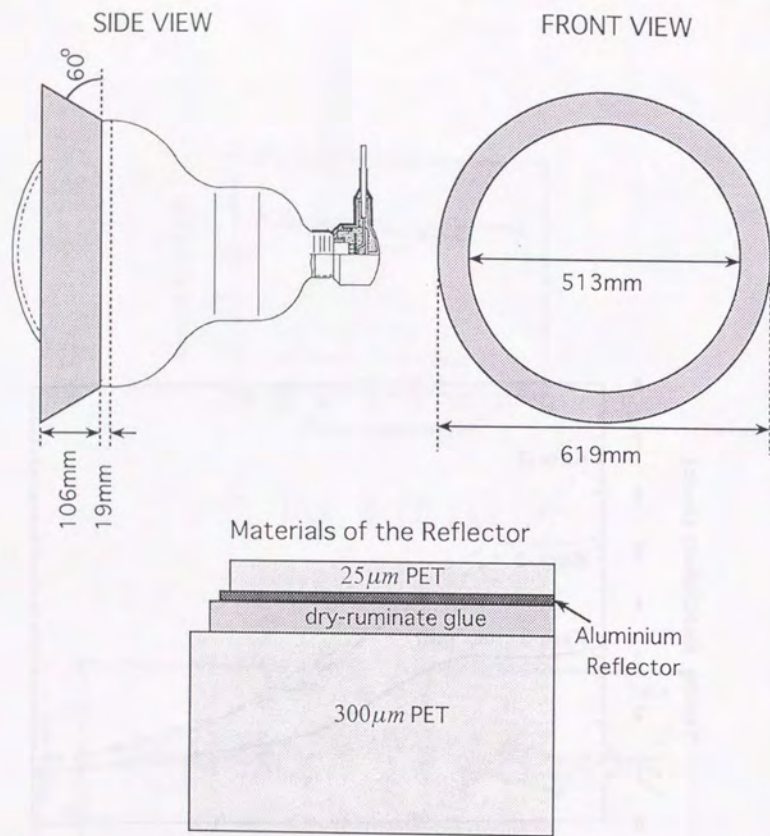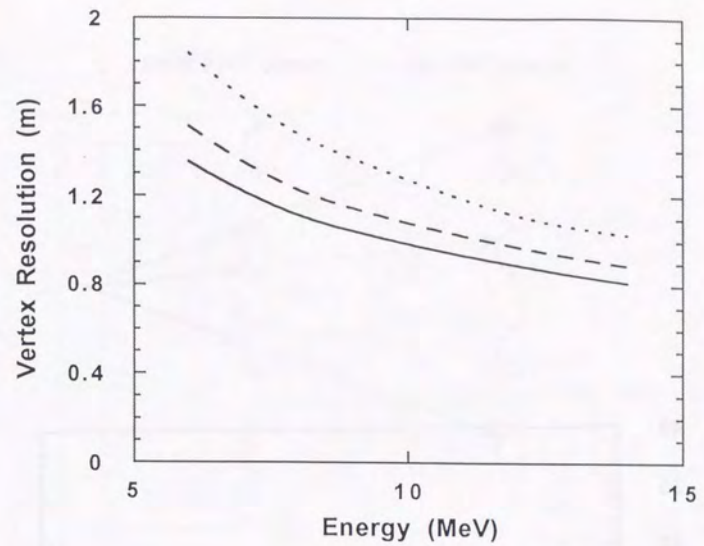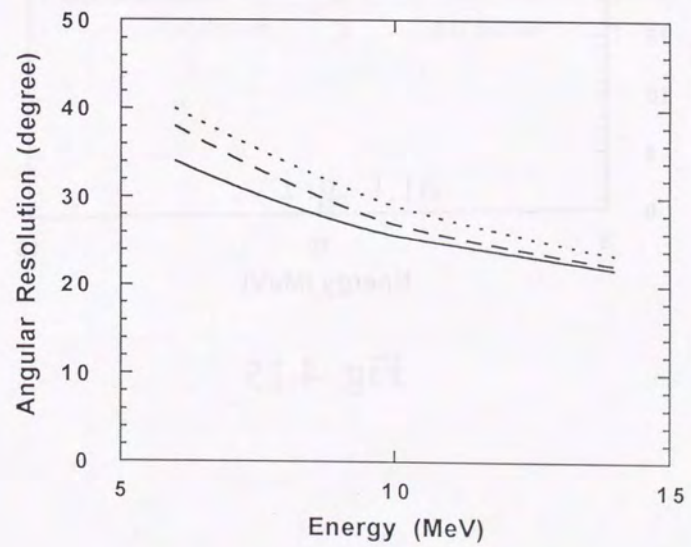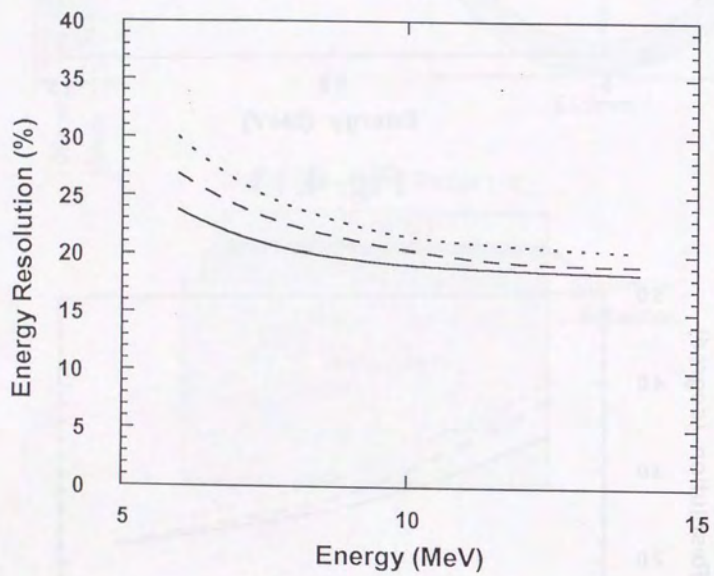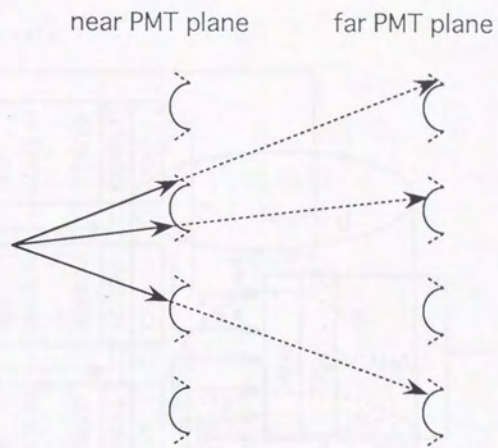
Kam-2	# of hit PMTs	2	# of hit PMTs	2
	# of photons	2	# of photons	2
Kam-3	# of hit PMTs	2	# of hit PMTs	3
	# of photons	3	# of photons	3

Fig. 4.16
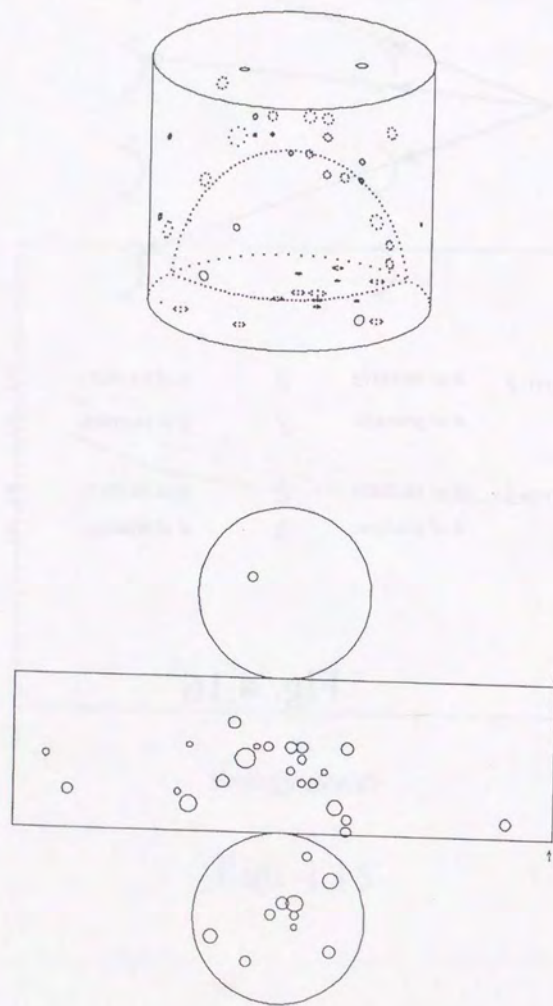
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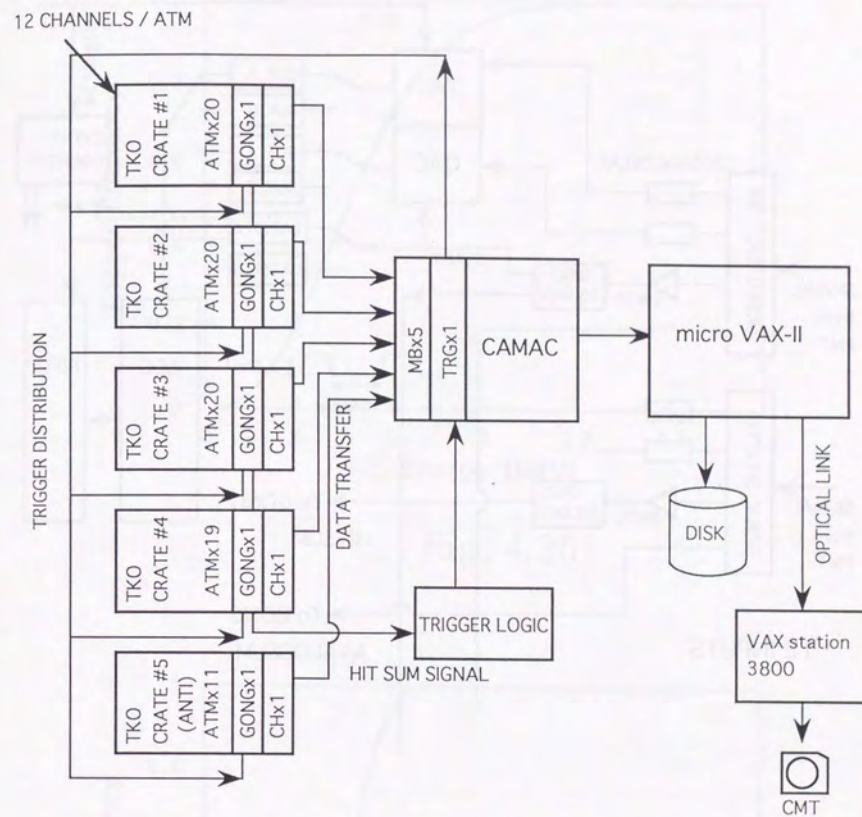
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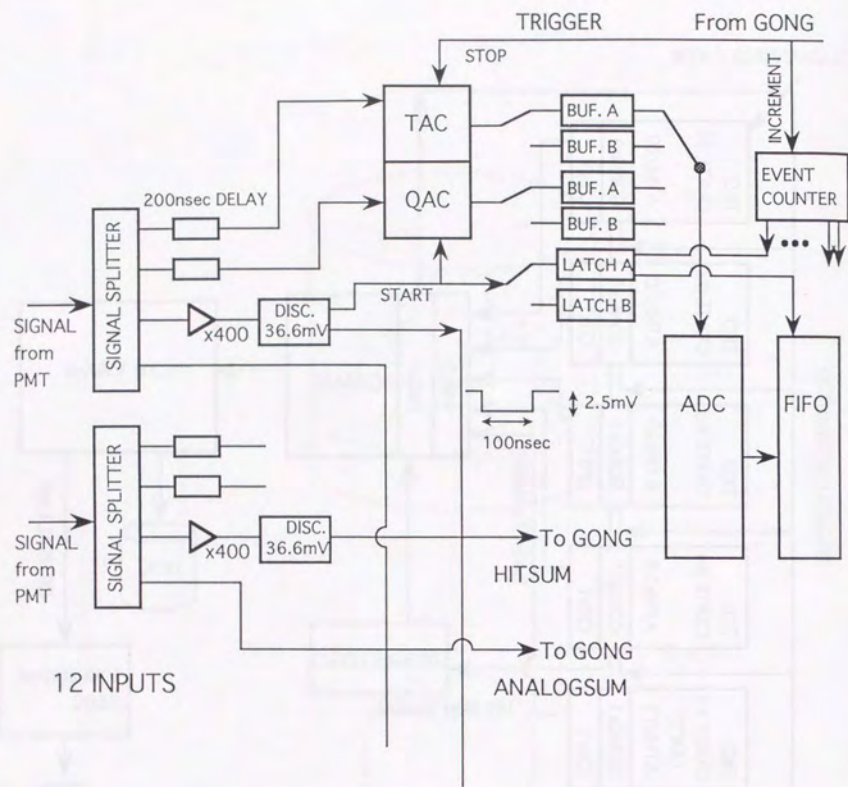
Fig. 4.19

Fig. 4.20

Fig. 4.21

Fig. 4.22 (left)

KAM-2 gainx1   KAM-2 gainx2   KAM-3

Trigger (Analysis) Threshold (MeV)

12
10
8
6
4
2
0

1987 1988 1989 1990 1991 1992 1993

Fig. 4.22

Fig. 4.23 (right)

U-Ra series

92 U ^{238}U β ^{234}U
       4.468e9y   99+%   2.45e5y
       ^{234m}Pa
       1.175m
91 Pa $\alpha(\gamma)$ $\beta(\gamma)$ IT 0.13% $\beta(\gamma)$
       ^{234}Pa $\alpha(\gamma)$
       6.75h
90 Th ^{234}Th ^{230}Th
       24.10d   8.0e4y
89 Ac $\alpha(\gamma)$
88 Ra ^{226}Ra
       1.60e3y
87 Fr $\alpha(\gamma)$
86 Rn ^{222}Rn ^{218}Rn
       3.824d β 3.5e-2s
85 At $\alpha(\gamma)$ ^{218}At 0.1% $\alpha\gamma$
       β ~2s
84 Po ^{218}Po 0.0185% ^{214}Po ^{210}Po
       3.05m   99.9% α 1.64e-4s   138.38d
       α ^{214}Bi $\beta\gamma$ α ^{210}Bi β
83 Bi 99+%   19.7m   99+%   5.012d   99+% $\alpha(\gamma)$
82 Pb ^{214}Pb $\beta\gamma$ α ^{210}Pb $\beta\gamma$ α ^{206}Pb
       26.8m   0.021%   22.3y   1.3e-4%   stable
81 Tl ^{210}Tl $\beta(\gamma)$ ^{206}Tl β
       1.30m   1.7e-6%   4.20m
80 Hg ^{206}Hg $\beta\gamma$
       8.1m

Th series

90 Th ^{232}Th ^{228}Th
       1.41e10y   1.913y
89 Ac $\alpha(\gamma)$ ^{228}Ac $\beta(\gamma)$ $\alpha\gamma$
       6.13h
88 Ra ^{228}Ra β ^{224}Ra
       5.76y   3.66d
87 Fr $\alpha(\gamma)$
86 Rn ^{220}Rn
       55.6s
85 At $\alpha(\gamma)$
84 Po ^{216}Po ^{212}Po
       0.15s $\beta\gamma$ 3.05e-7s
83 Bi α ^{212}Bi 64.0% α
       60.60m
82 Pb ^{212}Pb β 36.0% α ^{208}Pb
       10.64h   stable
81 Tl ^{208}Tl $\beta\gamma$
       3.053m

Fig. 4.23

water purification system

3000ton water tank

vacuum degasifier

membrane degasifier

F5 F4

UV-sterilizer

F3

purified water tank

radium resin

CR-55 (uranium resin)

mine water

F1

primary water tank

F2

de-ionization system
or
mixed bed ion-exchanger

charcoal

membrane dryer

membrane dryer

air dryer

charcoal

cooled charcoal

cooled charcoal

outlets

λ

radon-free air system

Fig. 4.24

events/hour

0.014pCi/l

Feb 93

Jan 93

Dec 92

Oct 91

Sep 91

Mar 91

Feb 91

Jan 91

0.1pCi/l

0.03pCi/l

40 30 20 10 0

Fig. 4.25

He

N₂

waste

vacuum
pump

flow (a)

inlet

Fig. 4.26

magnesium
perchlorate

He

pressure
gauge

ascarite

silica-gel

flow
meter

diaphragm
pump

cold trap

cold trap

vacuum
pump

Lucas cell

flow (b)

flow (c)

flow (d)

Swagelock connector

volume = 163ml

87mm

68mm

ZnS(Ag) paint

Lucite Window

56mm

58mm

Fig. 4.27

Fig. 4.28

Fig. 4.29

Fig. 4.30

Fig. 4.31

Detector No.1

^{214}Po

^{218}Po

^{210}Po

Count/Channel

ADC Channel

Fig. 4.32

to ADC

±15V

waterproof connector

battery

amplifier

stainless vessel

PIN photo-diode

570mm

stainless mesh

support plate

micro-porous film

150mm

250mm
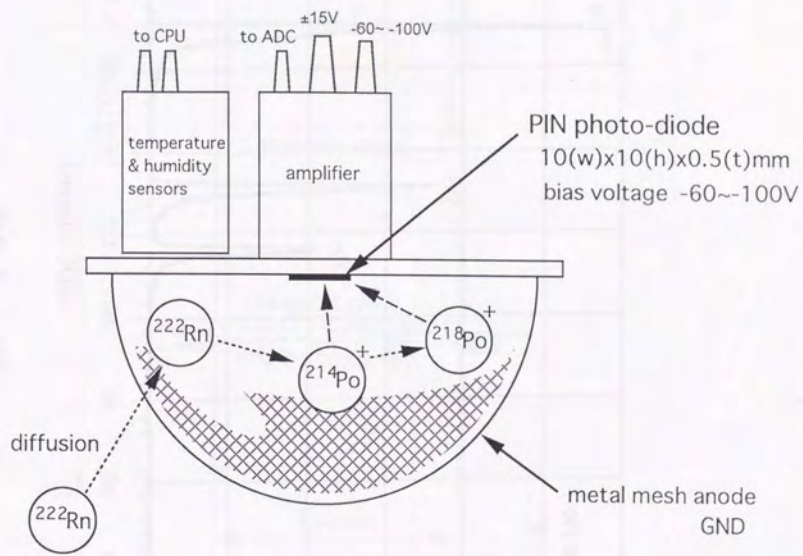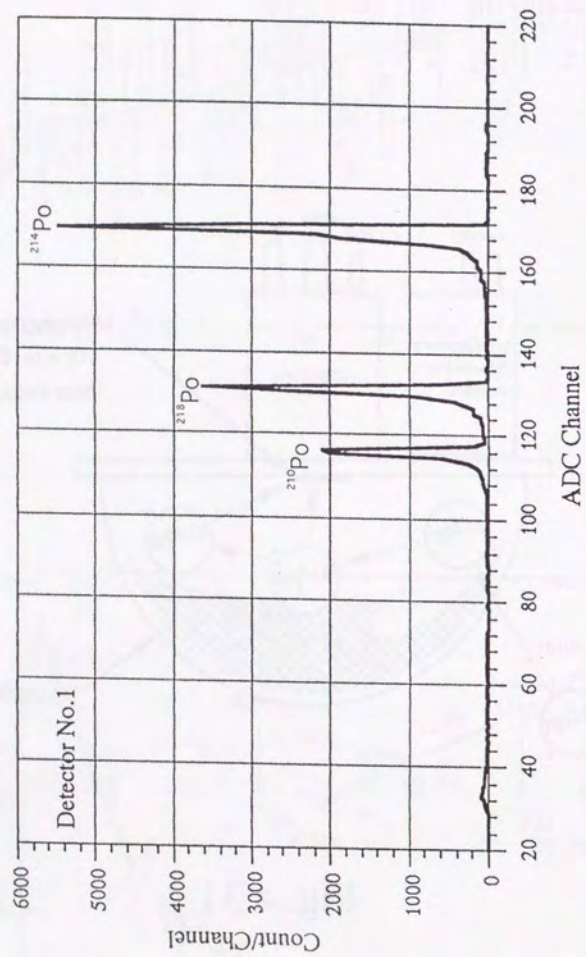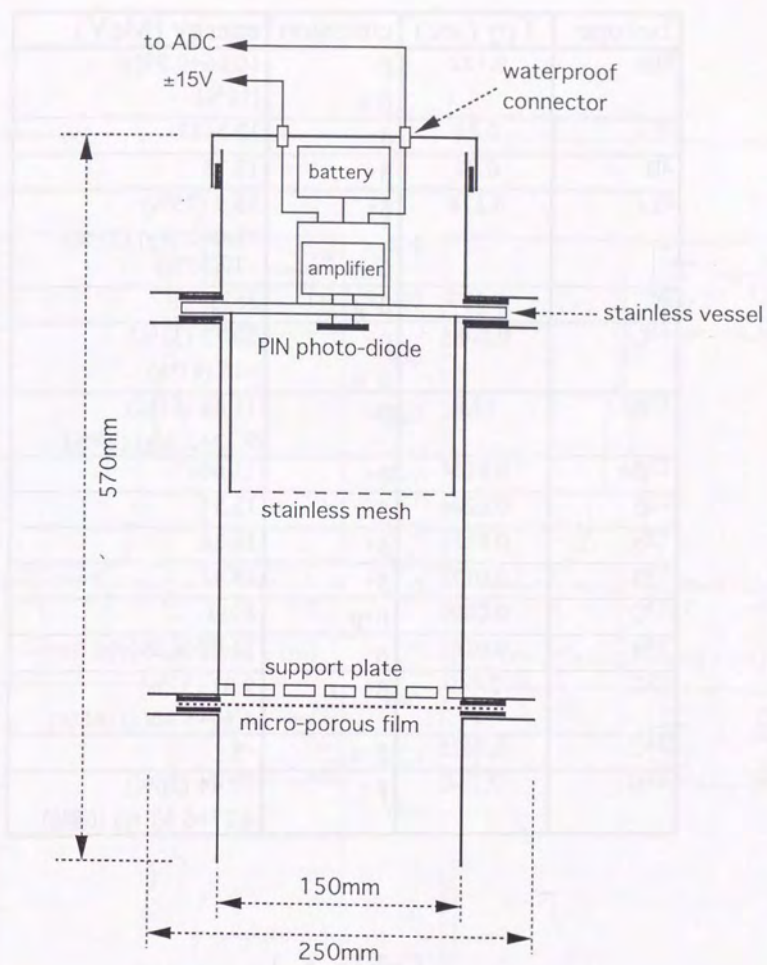
Fig. 4.33

Isotope	$T_{1/2}$ (sec)	emission	energy (MeV)
^{8}He	0.122	β– β–n	10.66+0.99(γ) (11%)
^{8}Li	0.84	β–	12.5~13
^{8}B	0.77	β+	13.73
^{9}Li	0.178	β– β–n	13.5 (75%) 11.0+2.5(γ) (25%) ~10(35%)
^{9}C	0.127	β+p	3~13
^{11}Li	0.0085	β– β–n	20.77 (31%) ~16 (61%)
^{11}Be	13.8	β–	11.48 (61%) 9.32+2.1(γ) (29%)
^{12}Be	0.0114	β–	11.66
^{12}B	0.0204	β–	13.37
^{12}N	0.0110	β+	16.38
^{13}B	0.0173	β–	13.42
^{13}O	0.0090	β+p	8~14
^{14}B	0.0161	β–	14.07+6.09(γ)
^{15}C	2.449	β–	9.82 (32%) 4.51+5.30(γ) (68%)
^{16}C	0.7478	β–n	~4
^{16}N	7.134	β–	10.44 (26%) 4.27+6.13 (γ) (68%)

Table 5.1

Fig. 5.1

Fig. 5.2

Fig. 5.3

Fig. 5.4

PMT used for vertex reconstruction

PMT used for direction reconstruction

Fig. 5.5

X (cm)

Z (cm)

MONTE CARLO
Te = 10 MeV
20 events

Fig. 5.6

relative amplitude (/0.1 p.e.)

photo-electrons

Fig. 5.7

Fig. 5.8

Fig. 5.9

anti—total p.e.

inner—total p.e.

Fig. 5.10

fiducial volume

r^2 (m²) vs z (m)

fiducial   cut

r^2 (m²) (−3.37<z<4.57m)

cut   fiducial   cut

z (m) (r<5.22m)
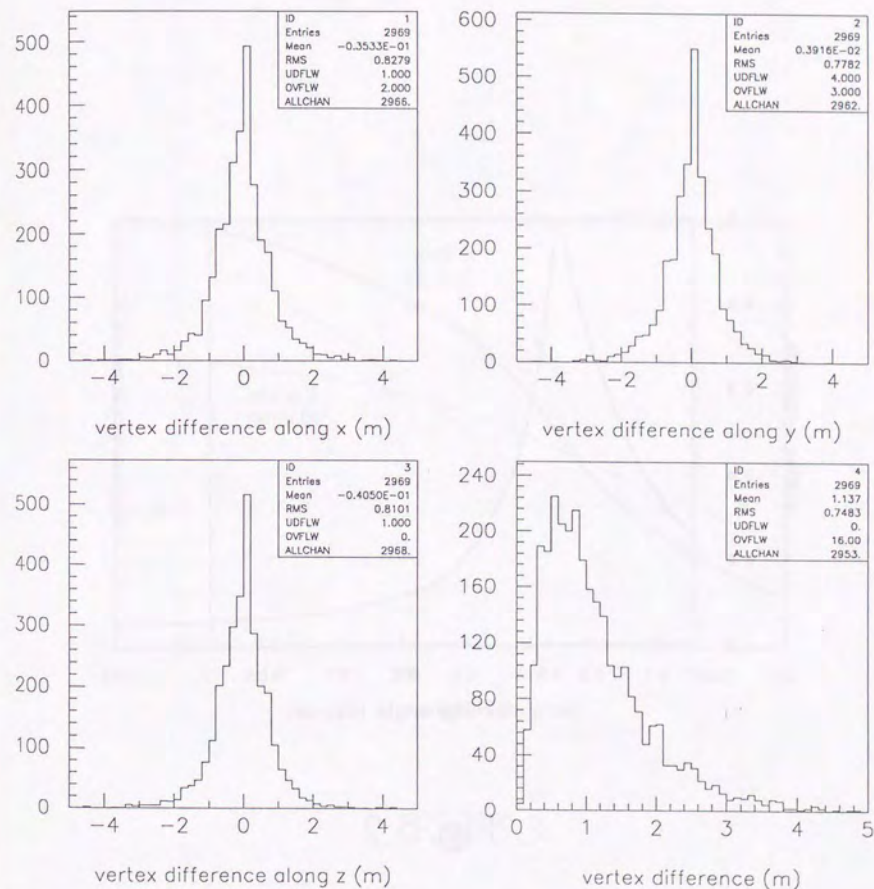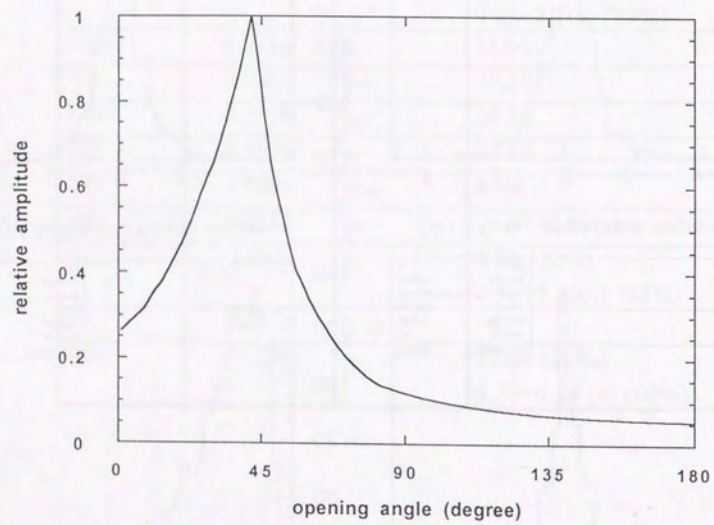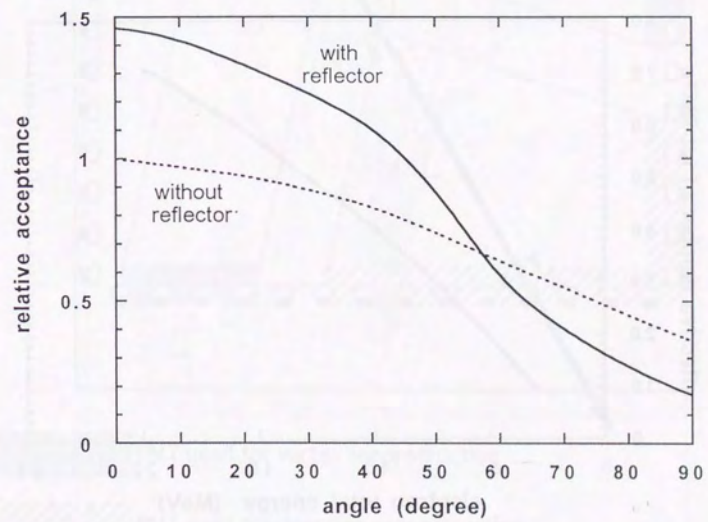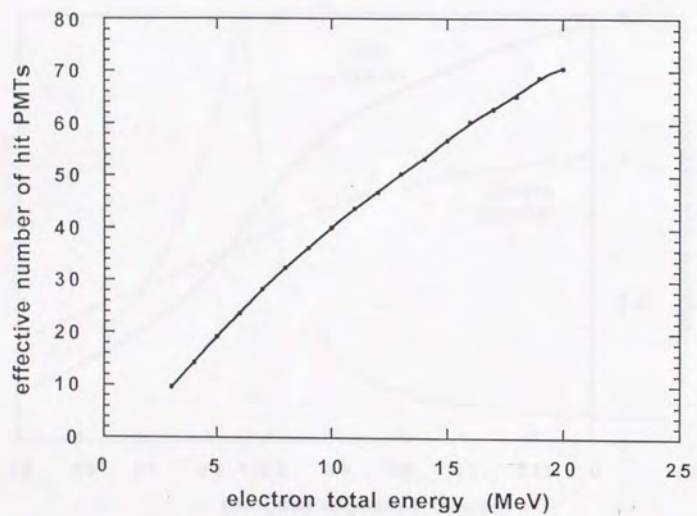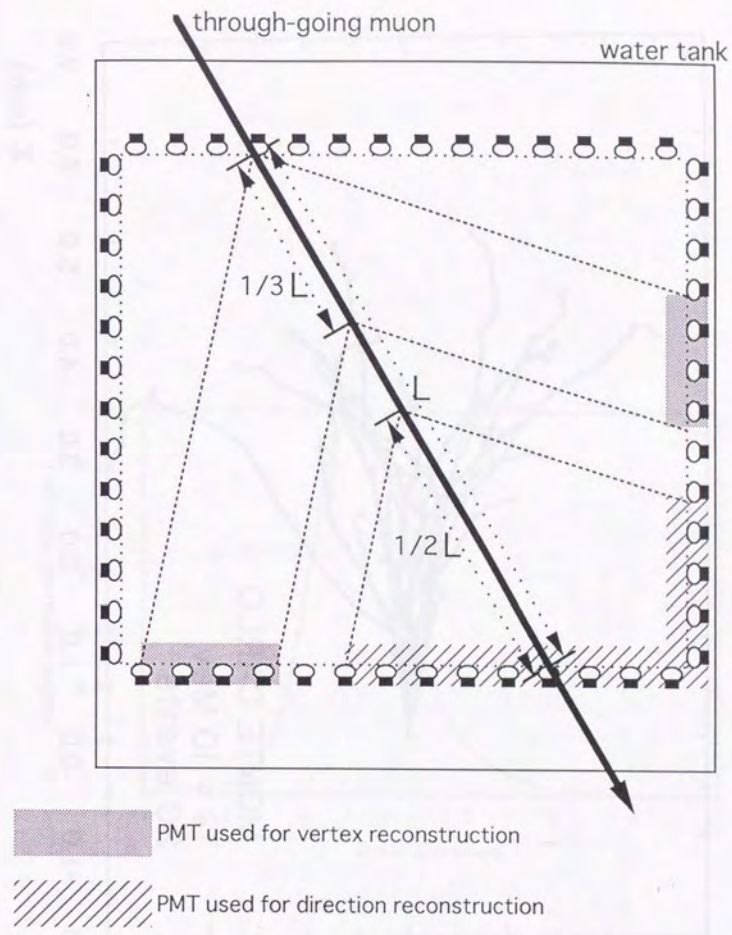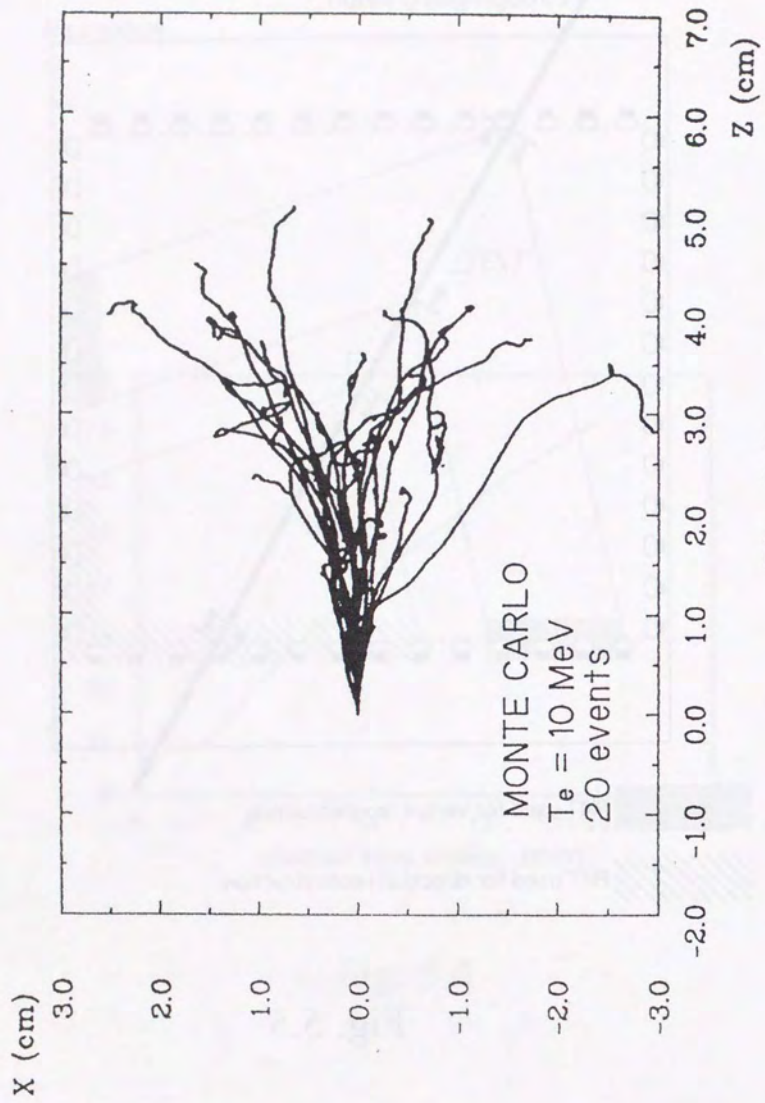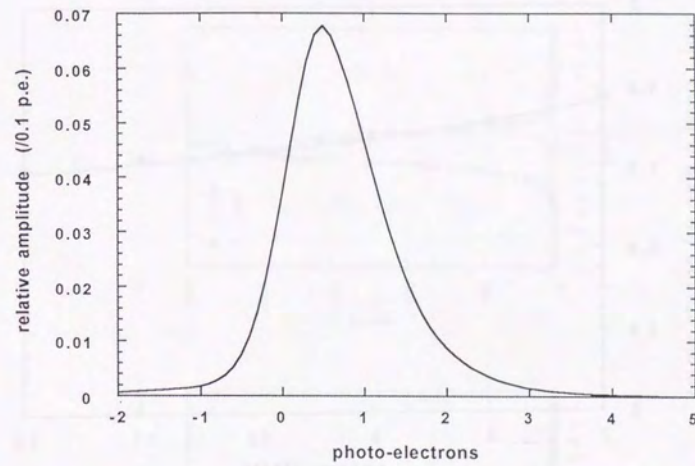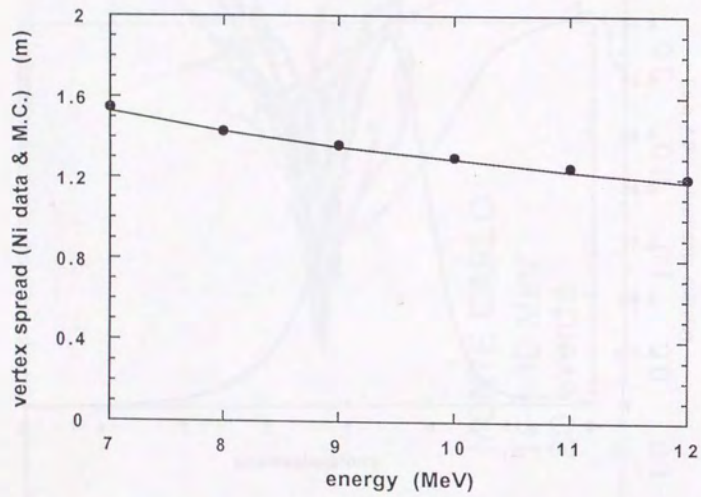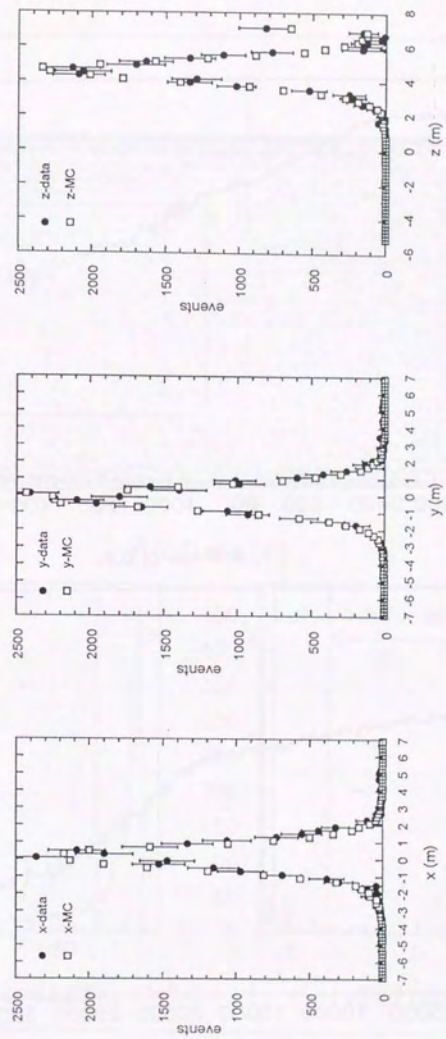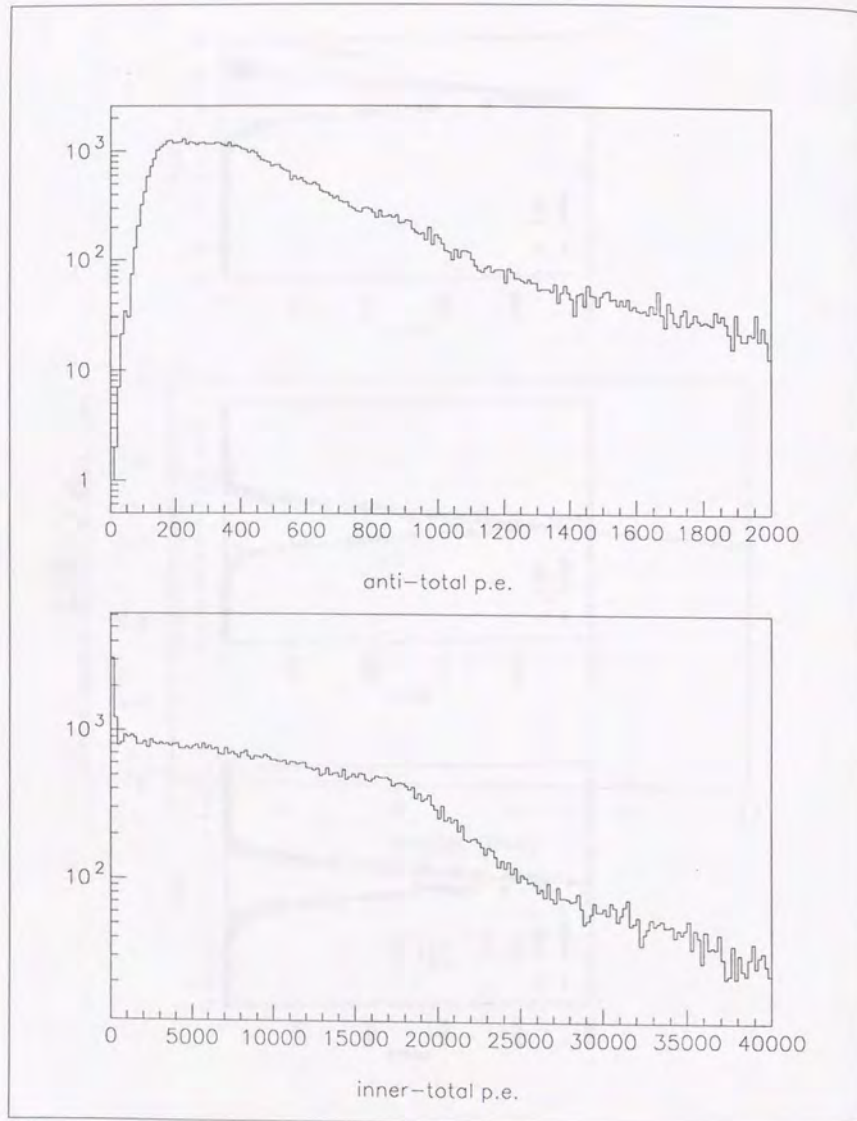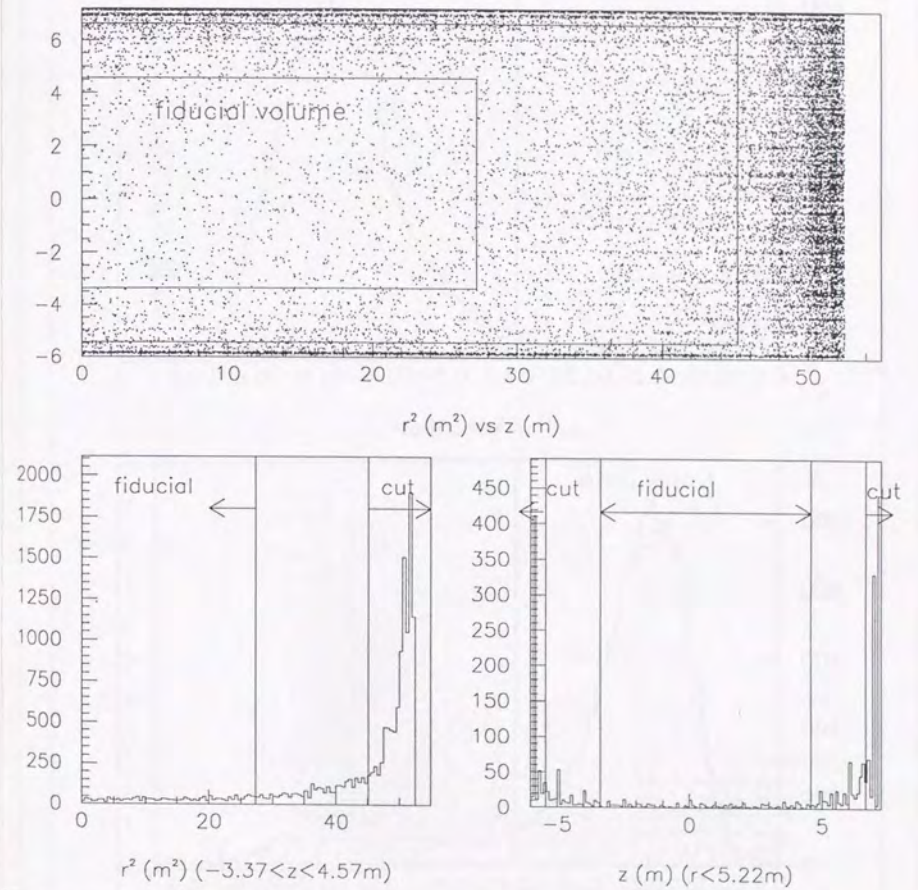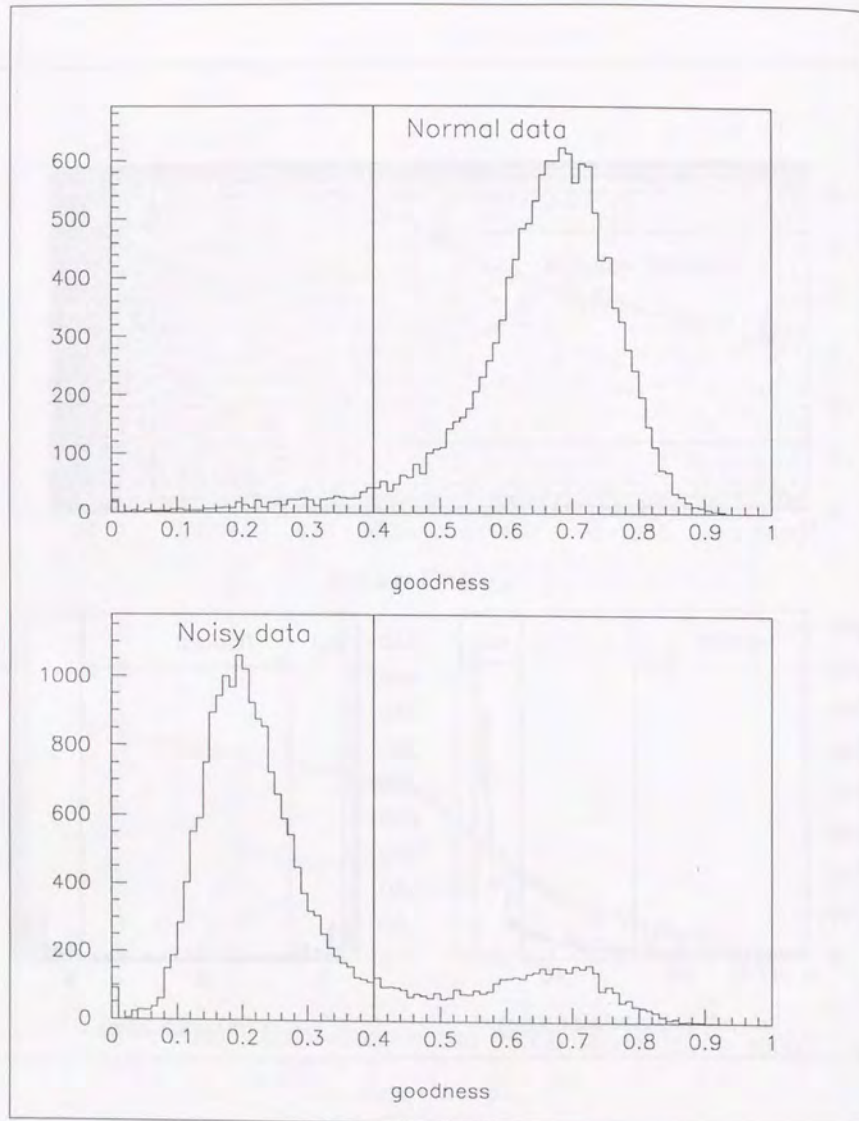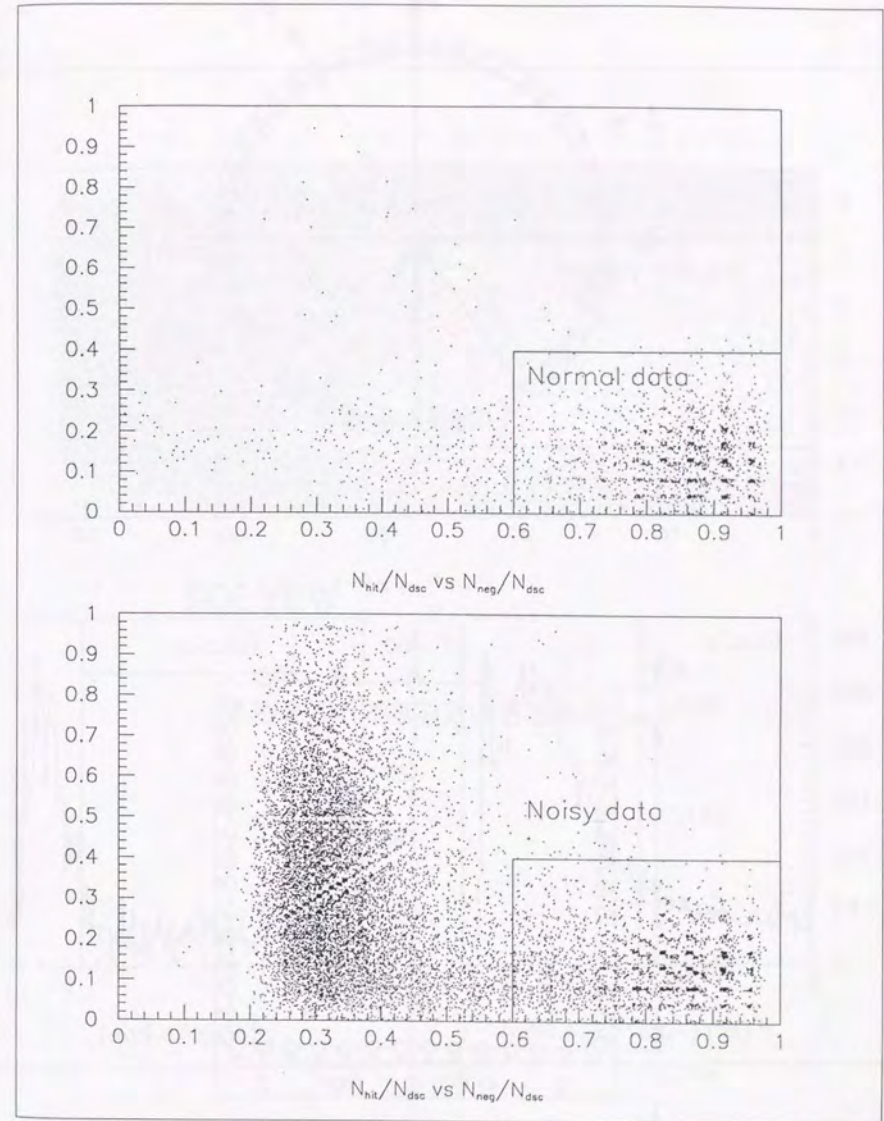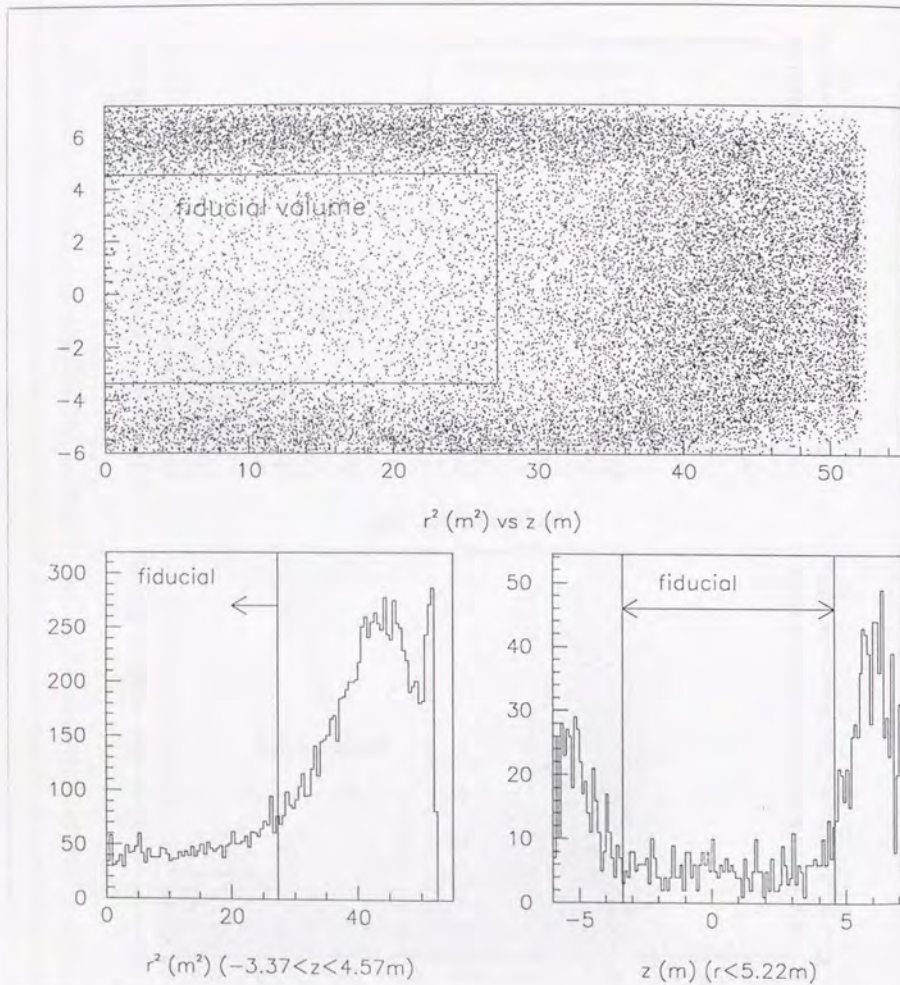
Fig. 5.11

Fig. 5.12

Fig. 5.13

Fig. 5.14
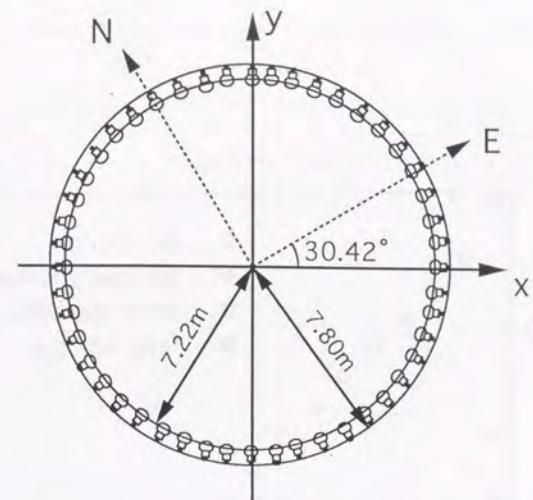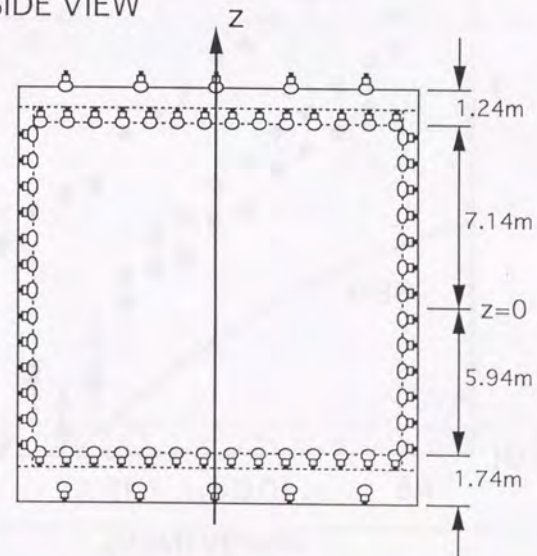
Fig. 5.15

Fig. 5.16

Fig. 5.17

Fig. 5.18

before spallation cut
$Q_{eff} \geqq 20000$ p.e.
$E_e \geqq 9$ MeV
$\Delta t < 1$ (sec)

ΔL (m)

Fig. 5.19

$$\chi^2/ndf \quad 72.47 \quad / \quad 56$$
$$P1 \quad 5.341$$
$$P2 \quad 2.996$$

$$dN/dt = P1 \times \exp(-t/10.29) + P2$$

Δt (sec)

ΔL (m)

Fig. 5.20

r^2 (m^2)

z (m)
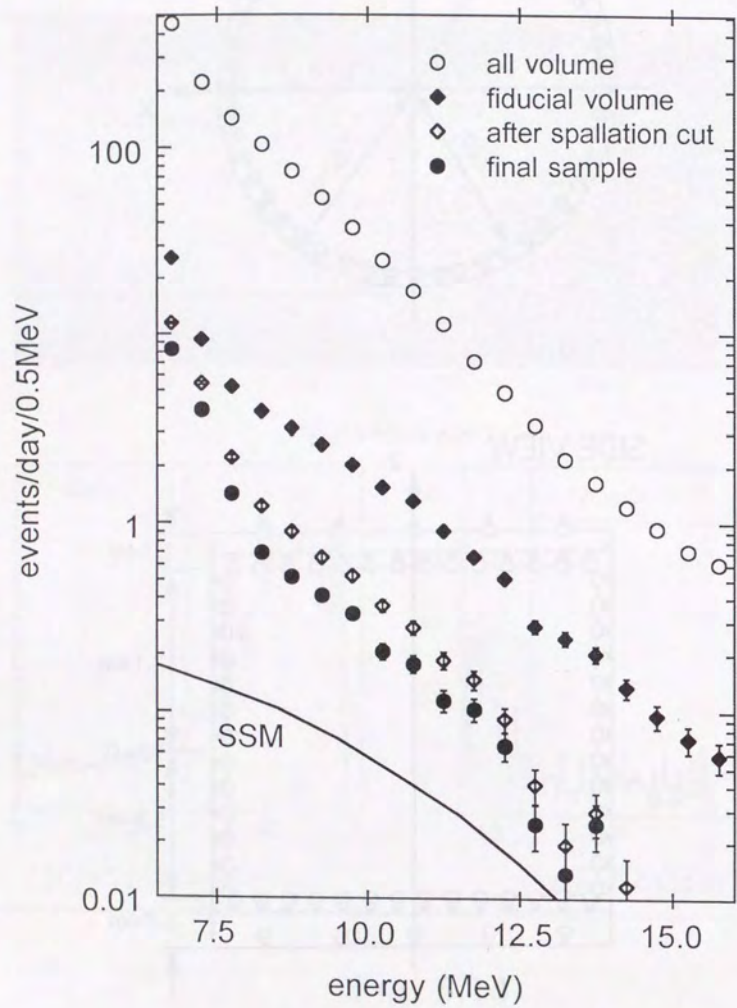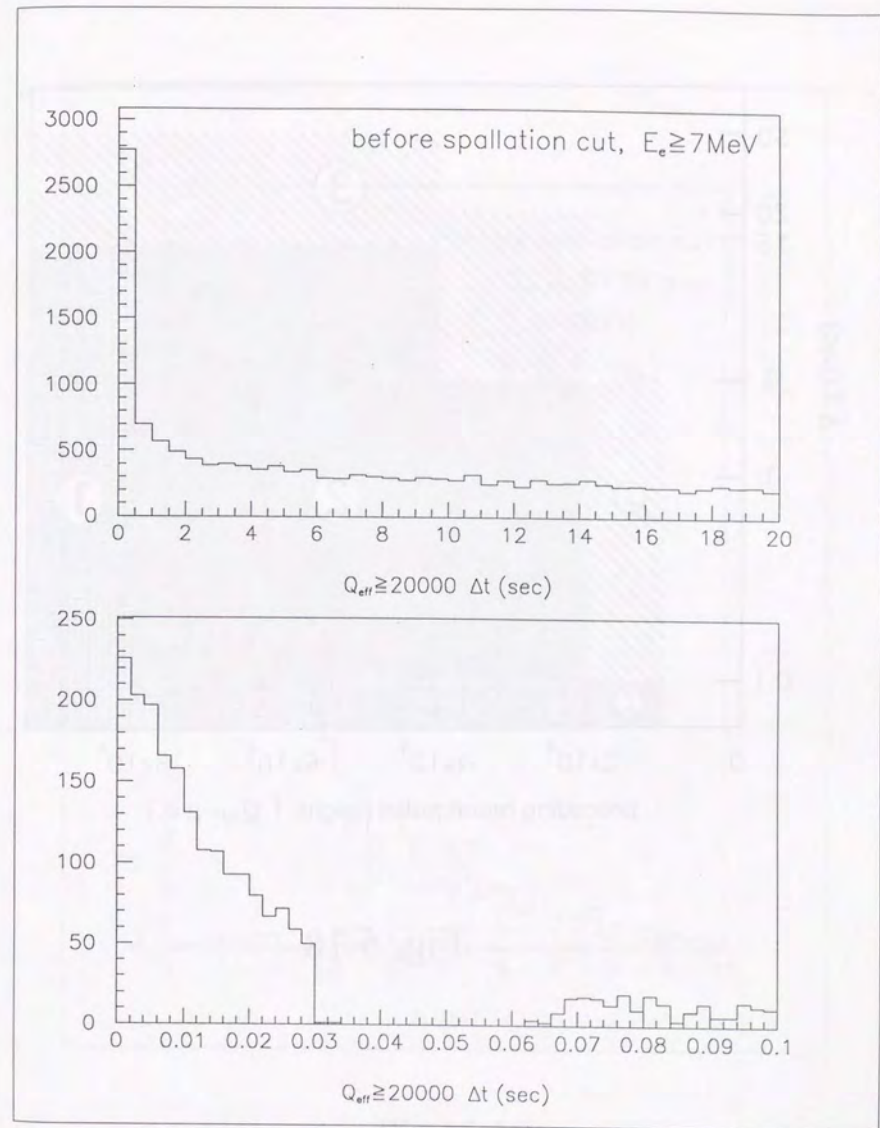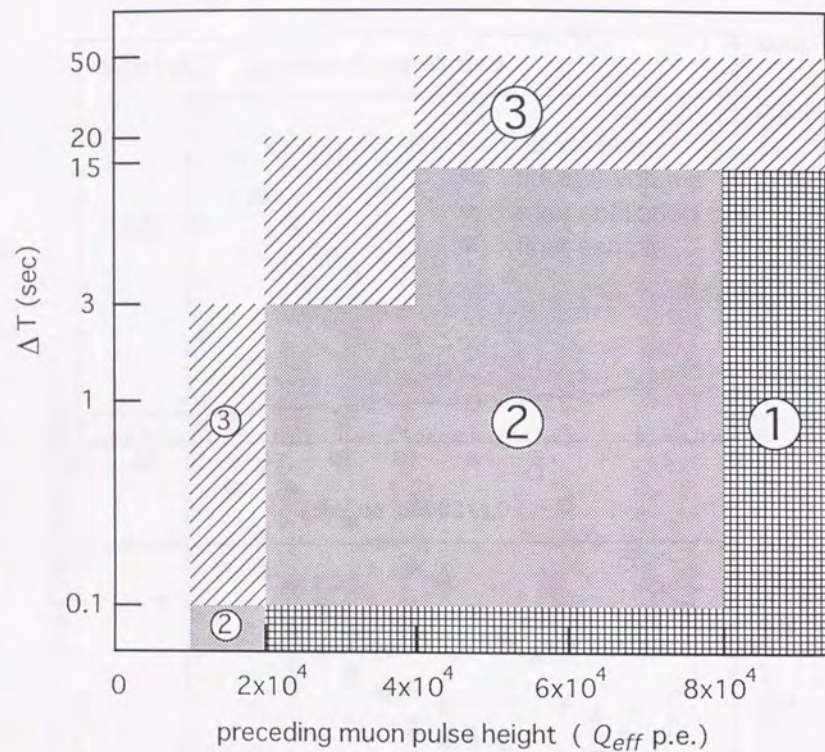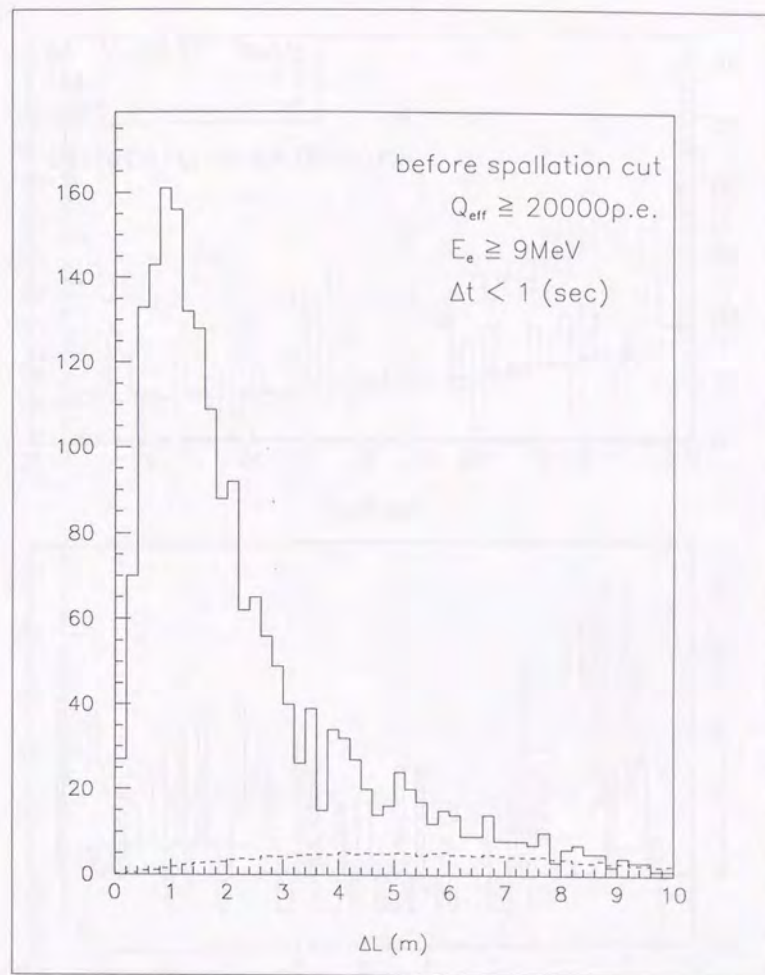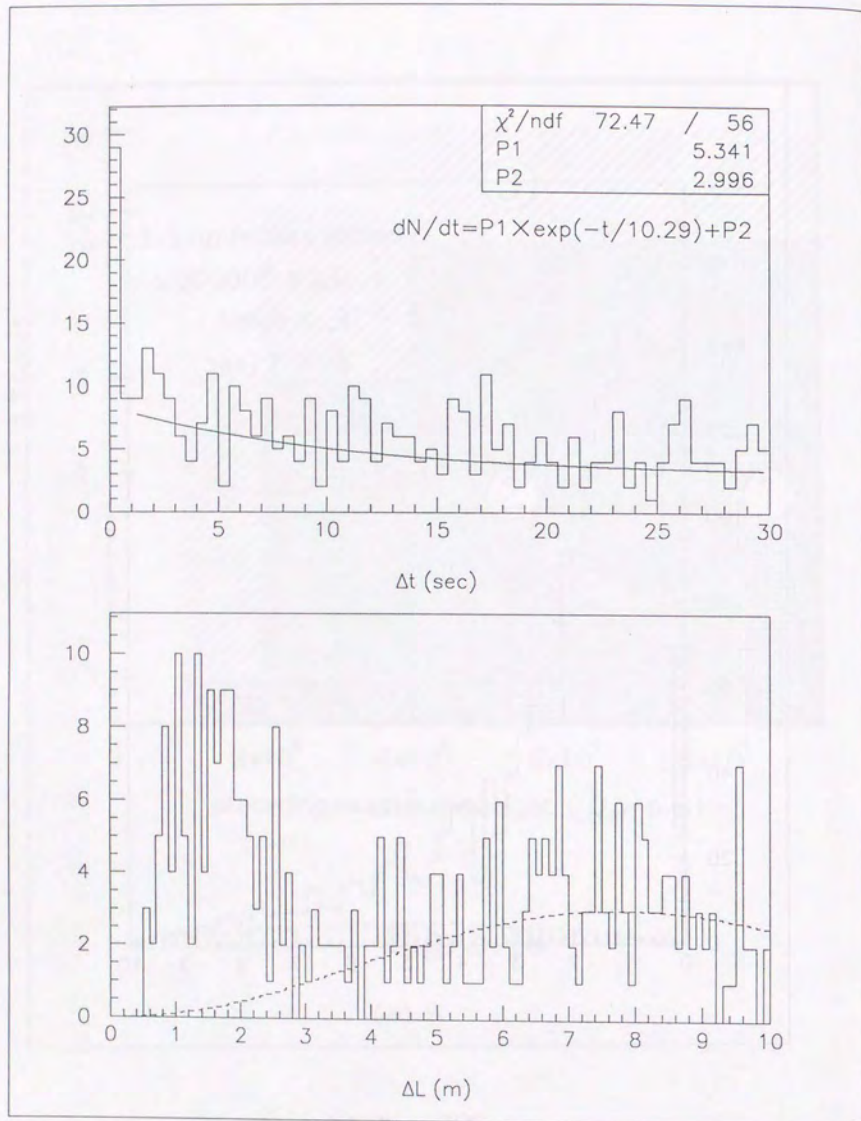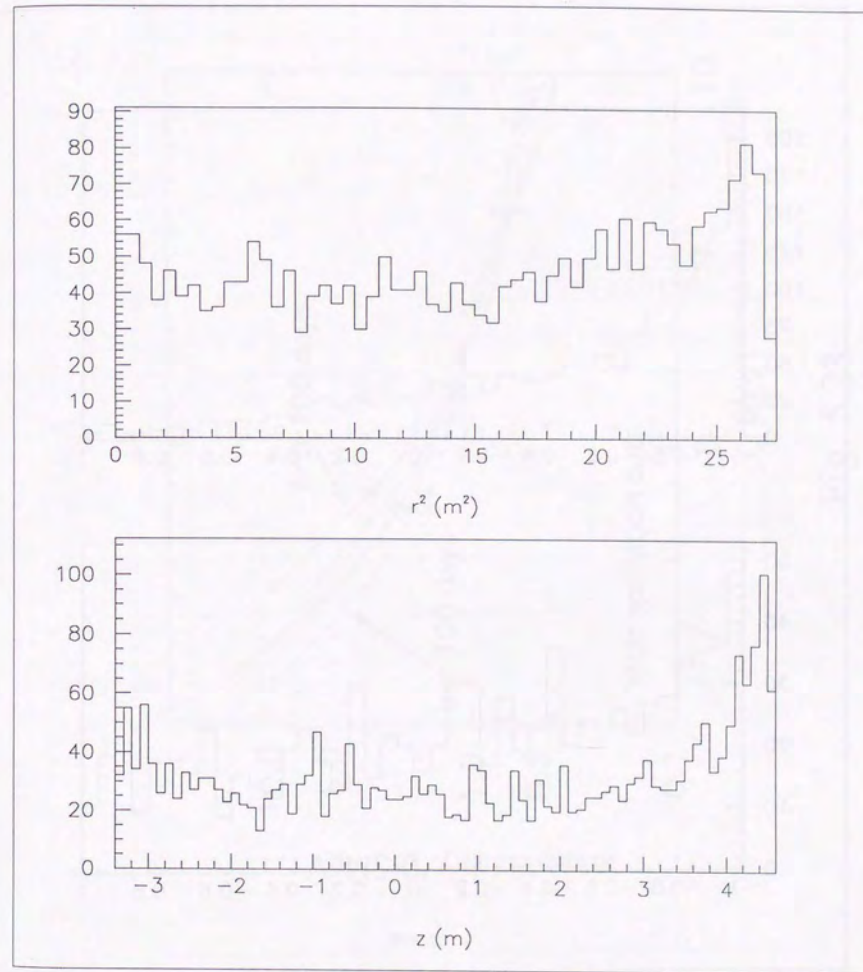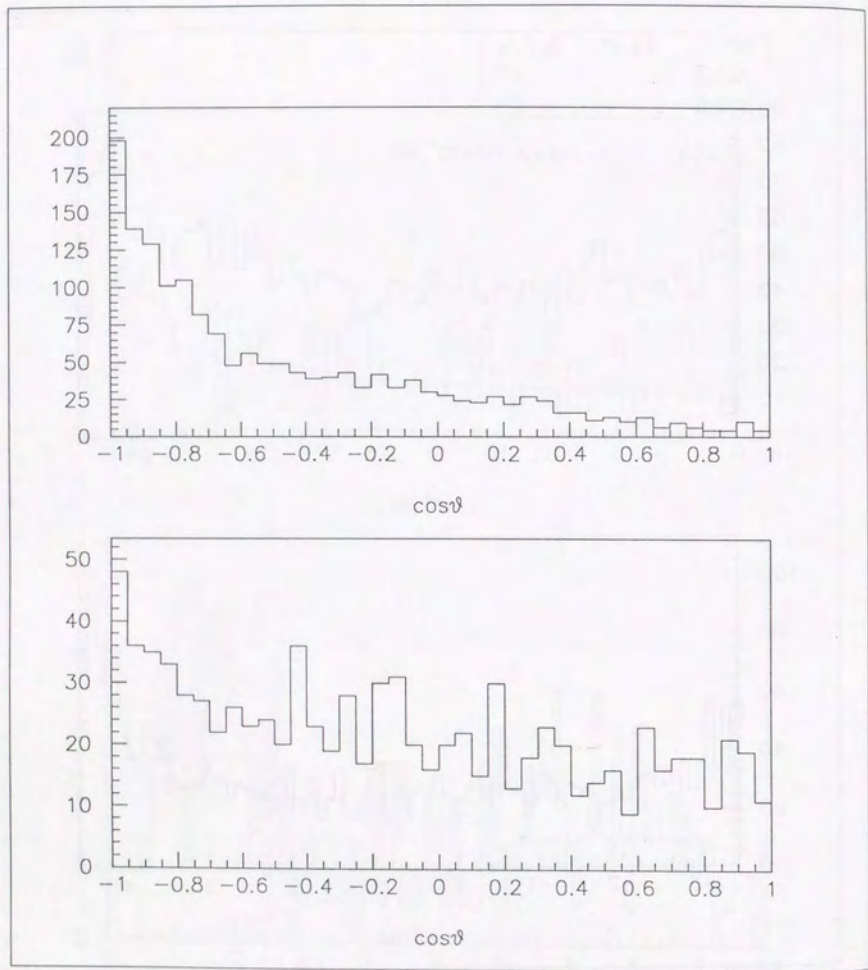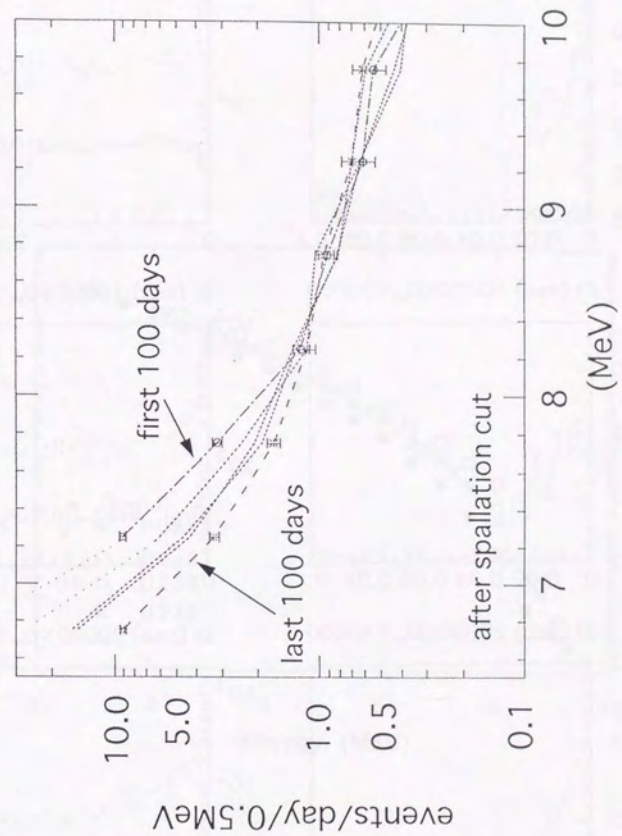
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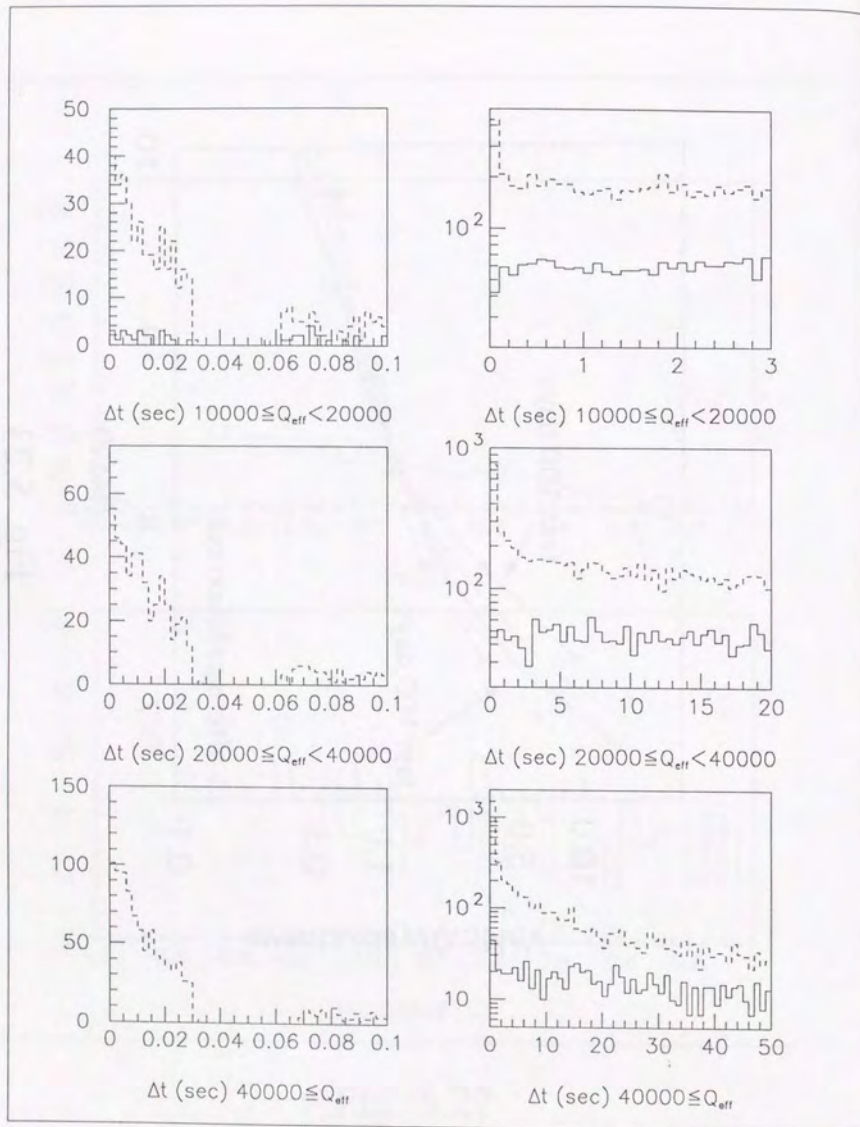
Fig. 5.22

Fig. 5.23

Fig. 5.24
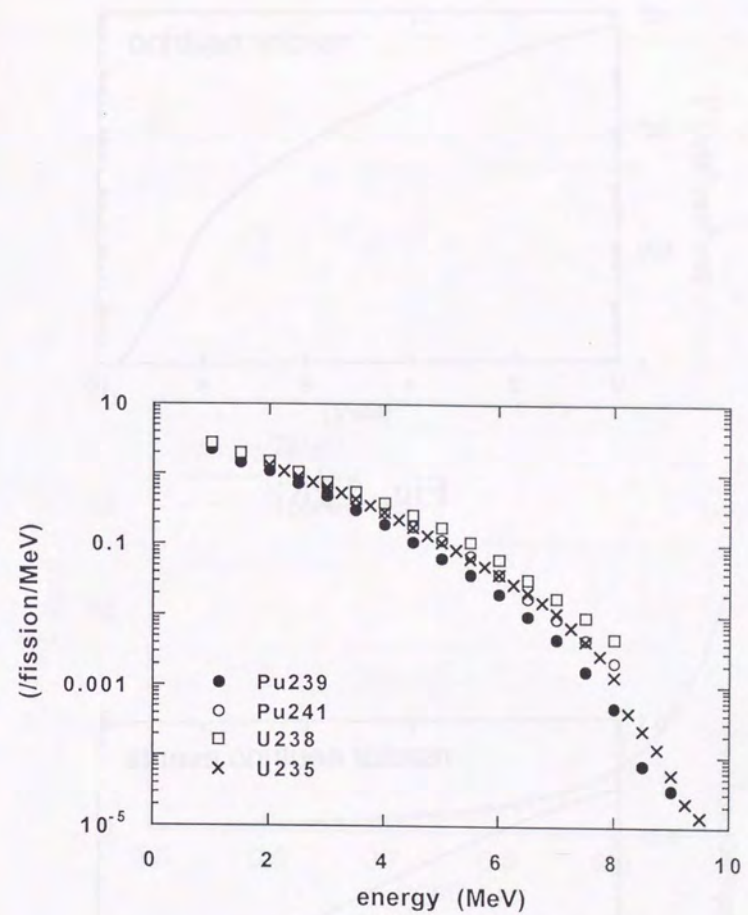
Fig. 5.25
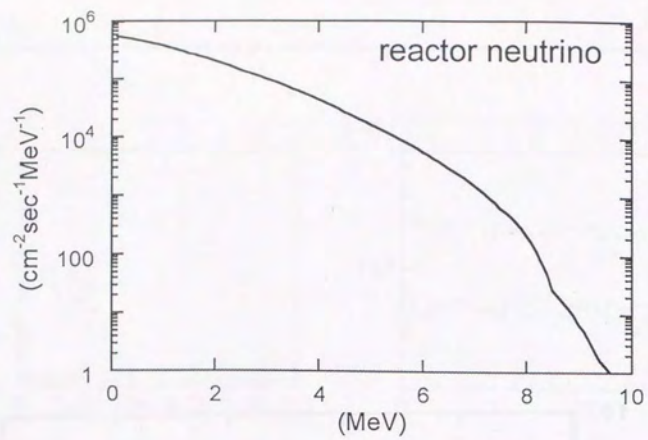
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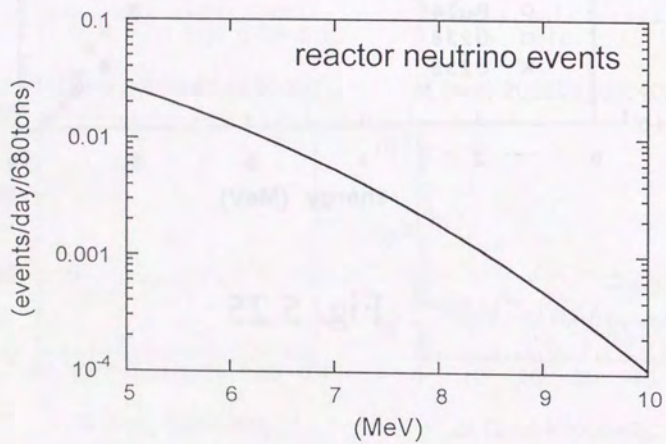
Fig. 5.27

Fig. 6.1

Fig. 6.2 (a)

Fig. 6.2 (b)

relative likelihood

(solar ν events / all events)

Fig. 6.3

(events/day)

(MeV)
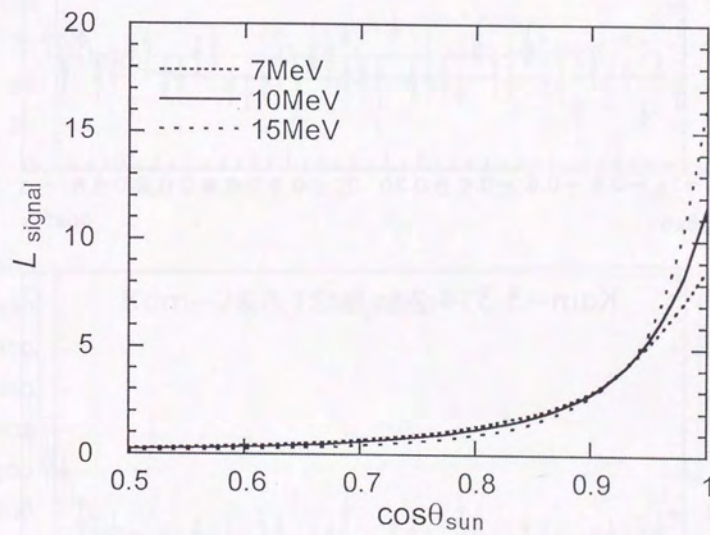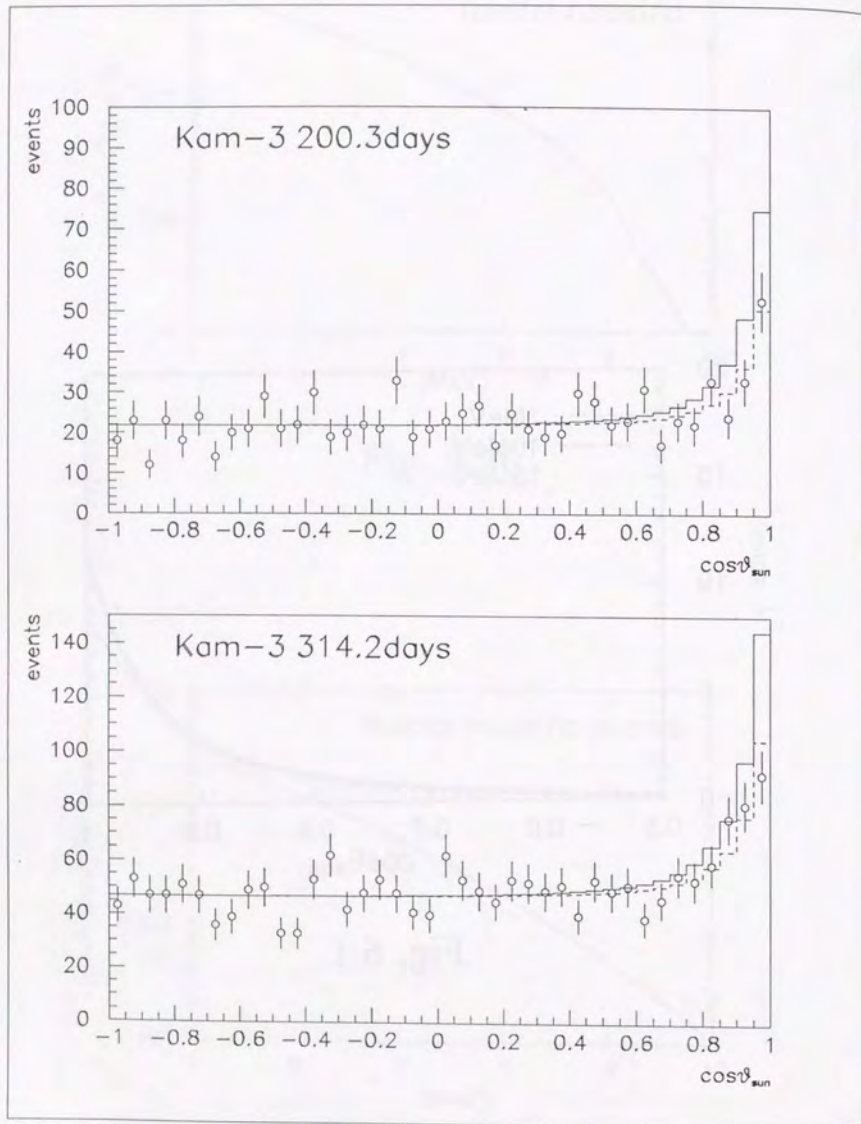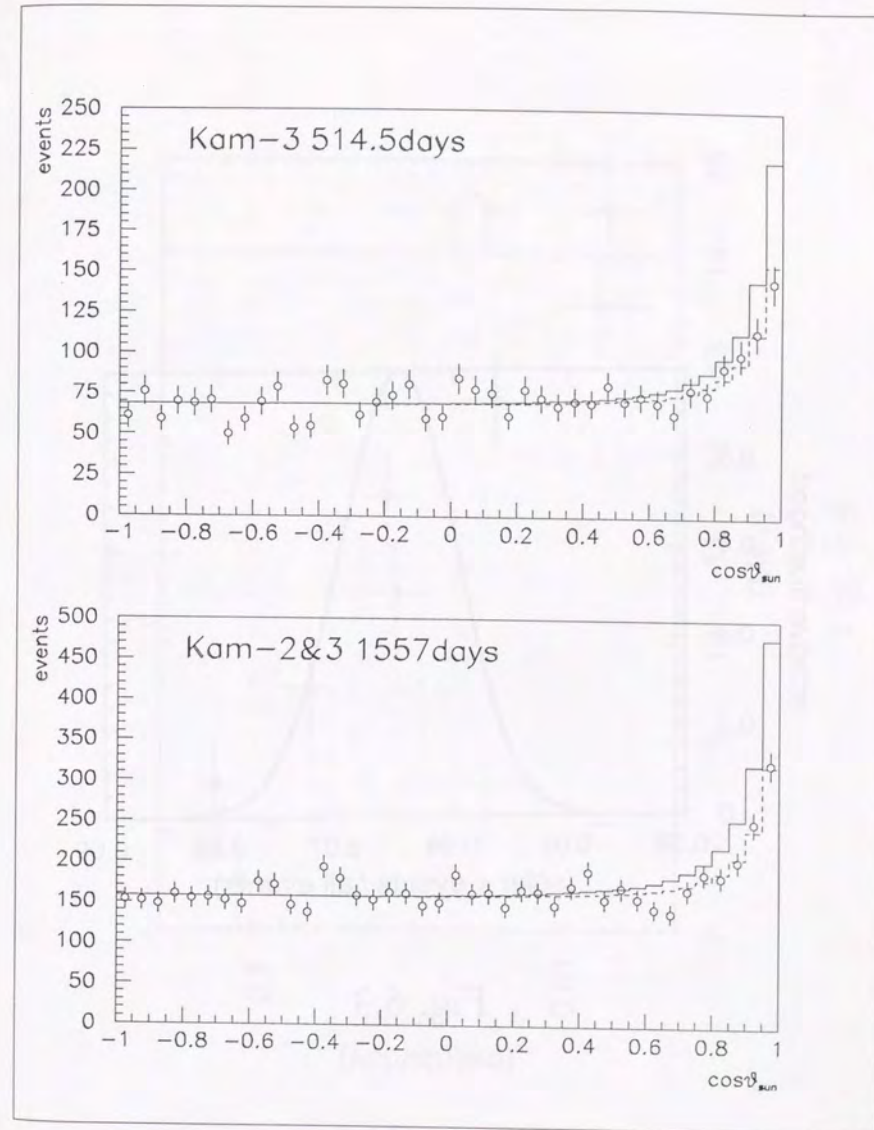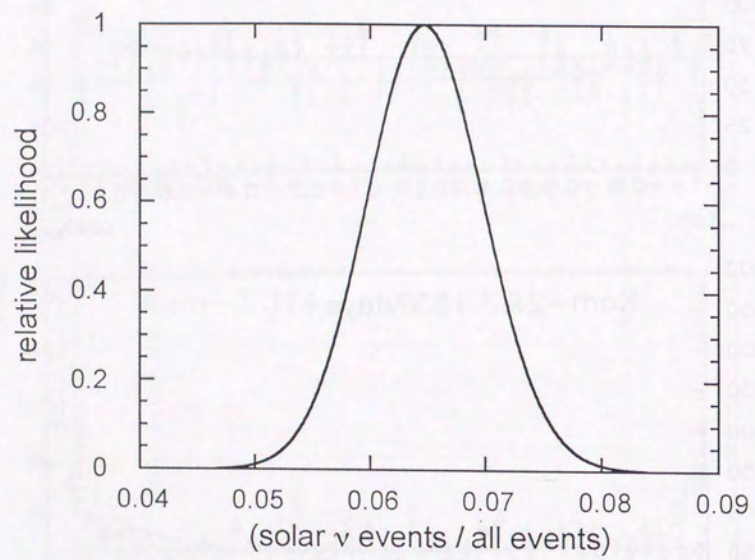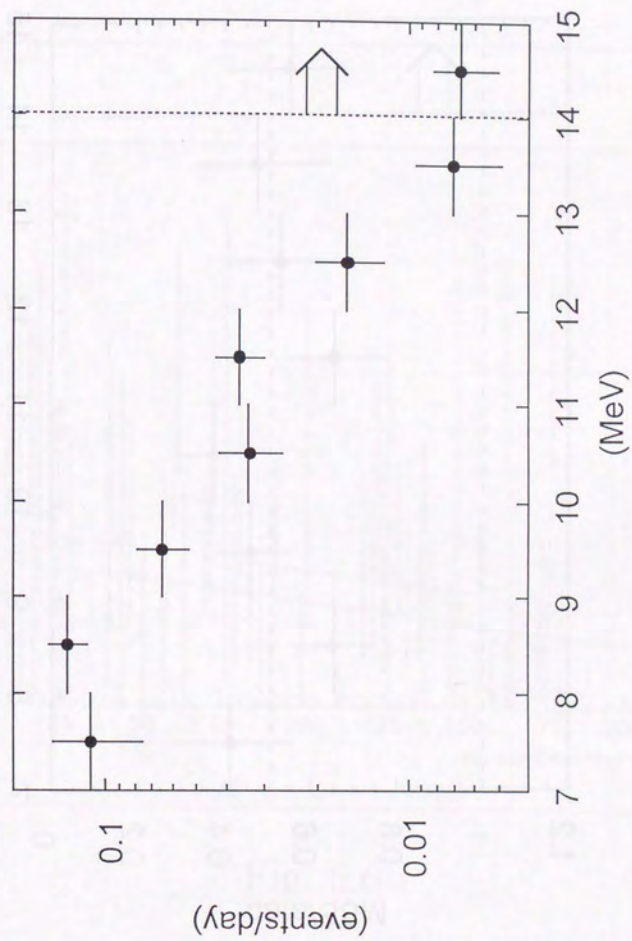
Fig. 6.4

Fig. 6.5

Fig. 6.6

Fig. 6.7

Fig. 6.8

different threshold

68% 90%

1σ   1σ

common threshold

68% 90%

1σ   1σ
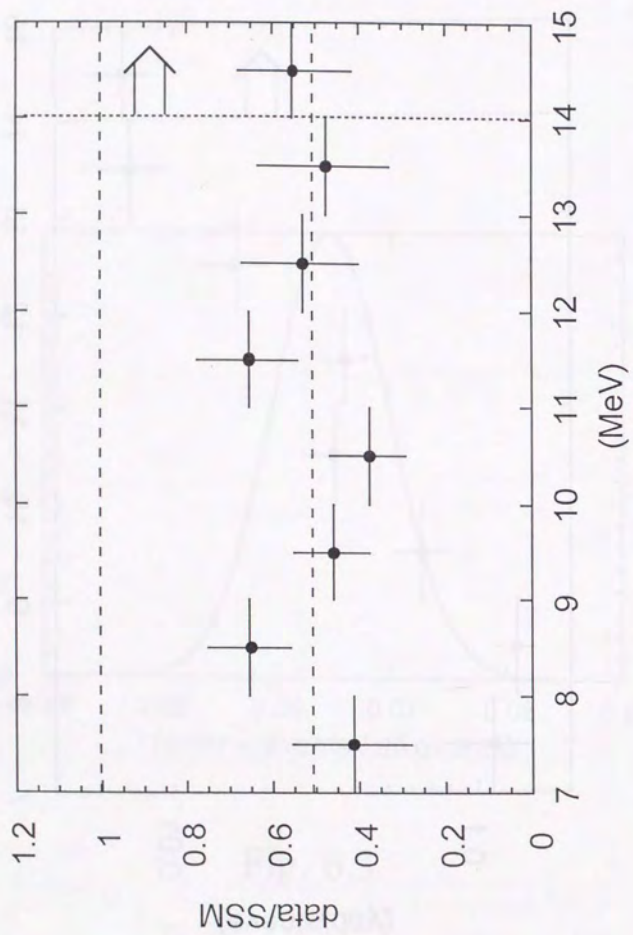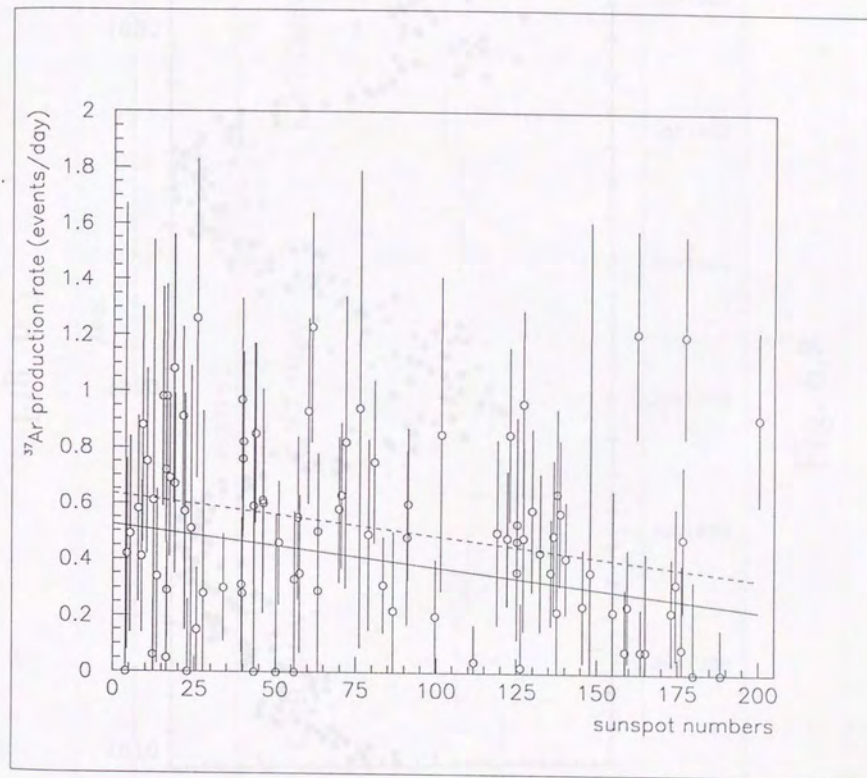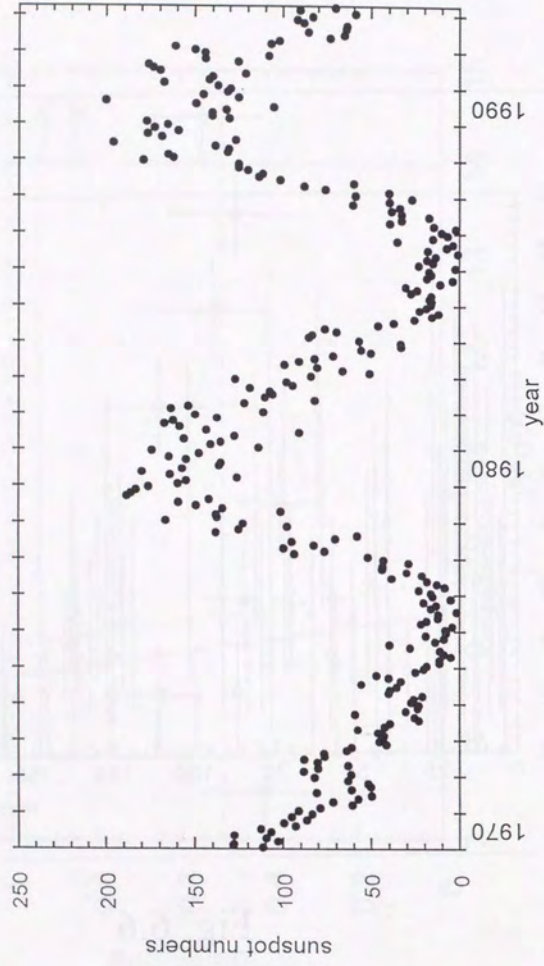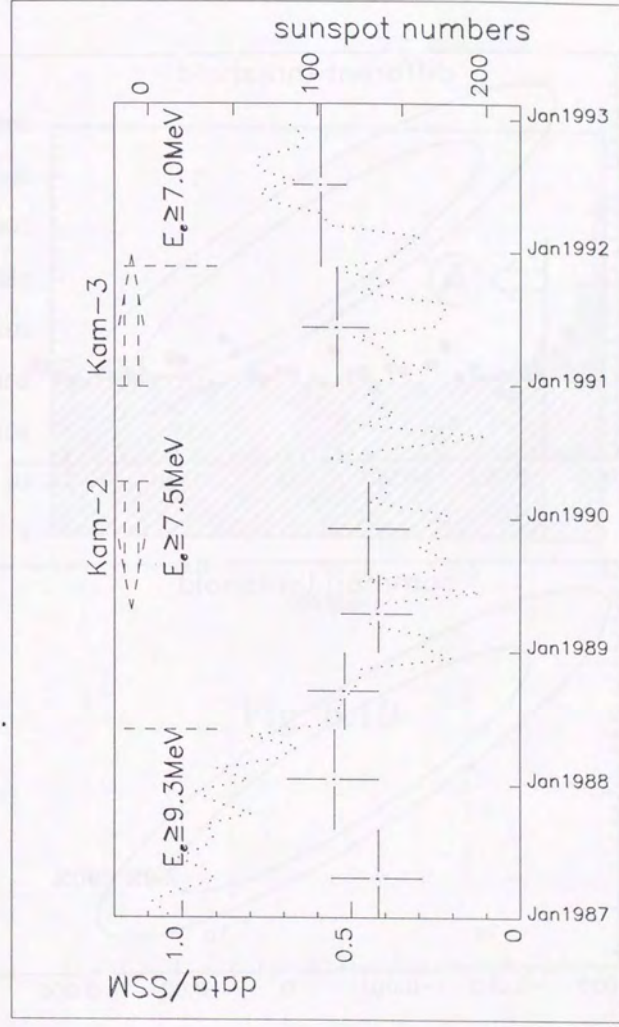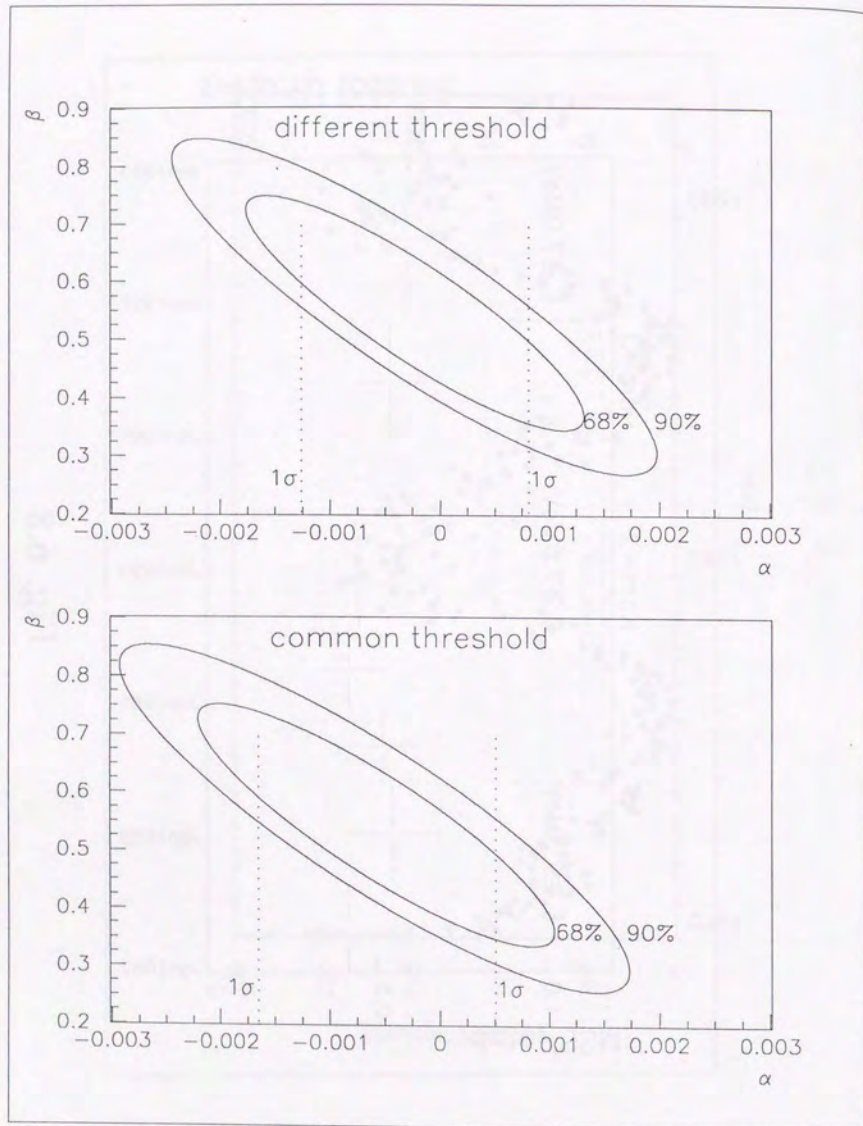
Fig. 6.9

Fig. 6.10

Fig. 6.11

Fig. 6.12

$\dfrac{\phi(\overline{\nu}_e)}{\phi(^8B)}$

(MeV)

90%C.L. upper limit

Fig. 6.13

Kamioka 90%C.L.

$\log(\delta m^2\,[eV^2])$

$\log(\sin^2 2\vartheta)$
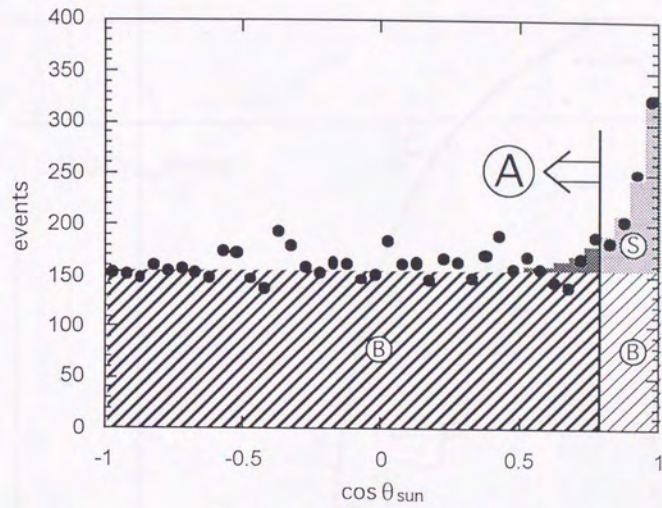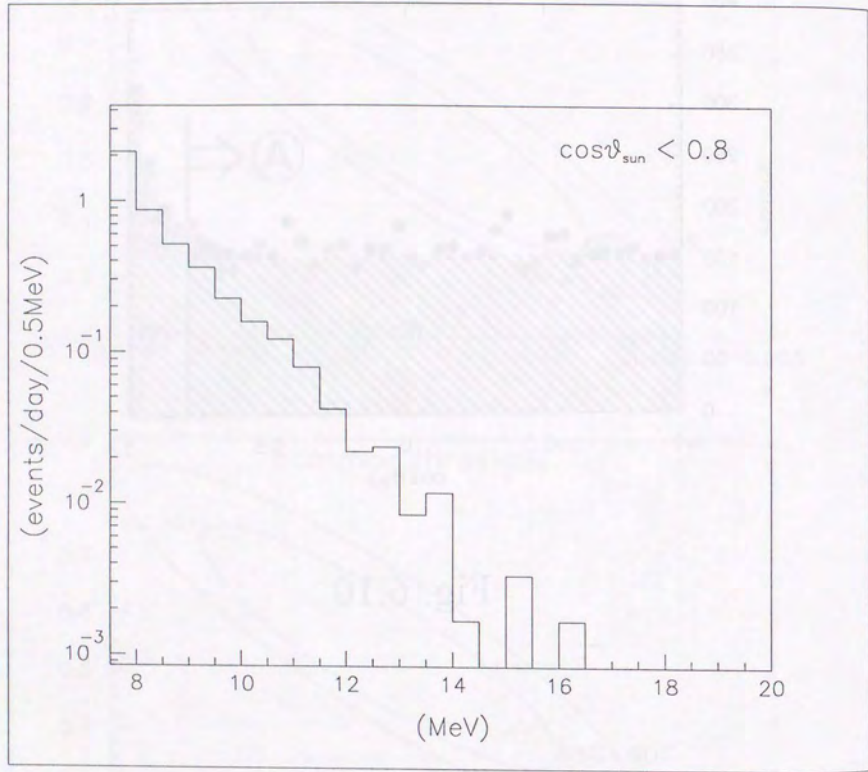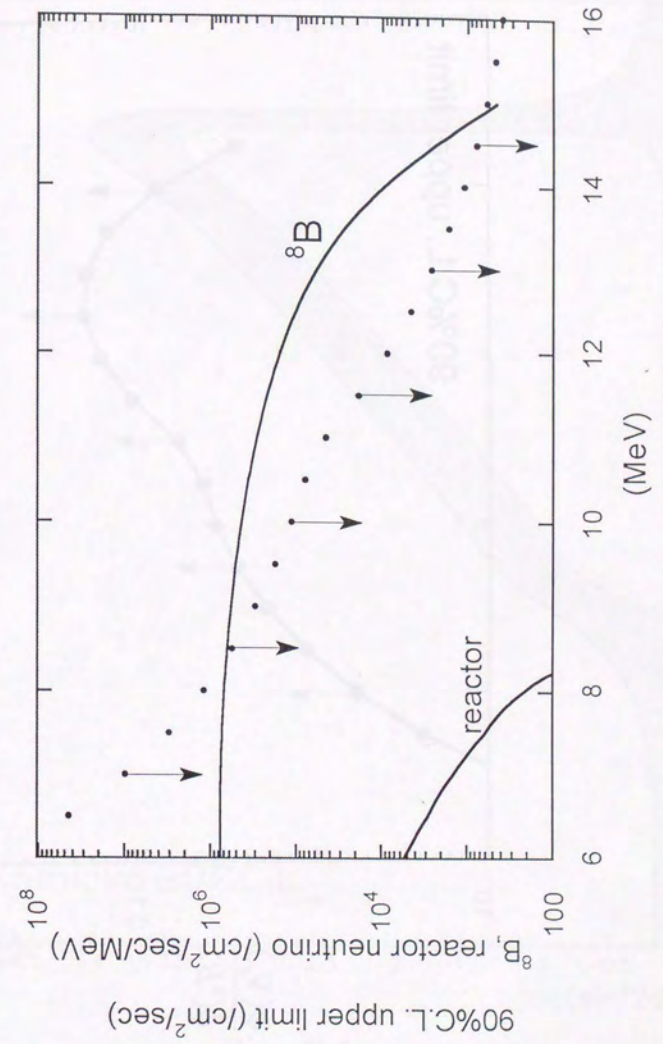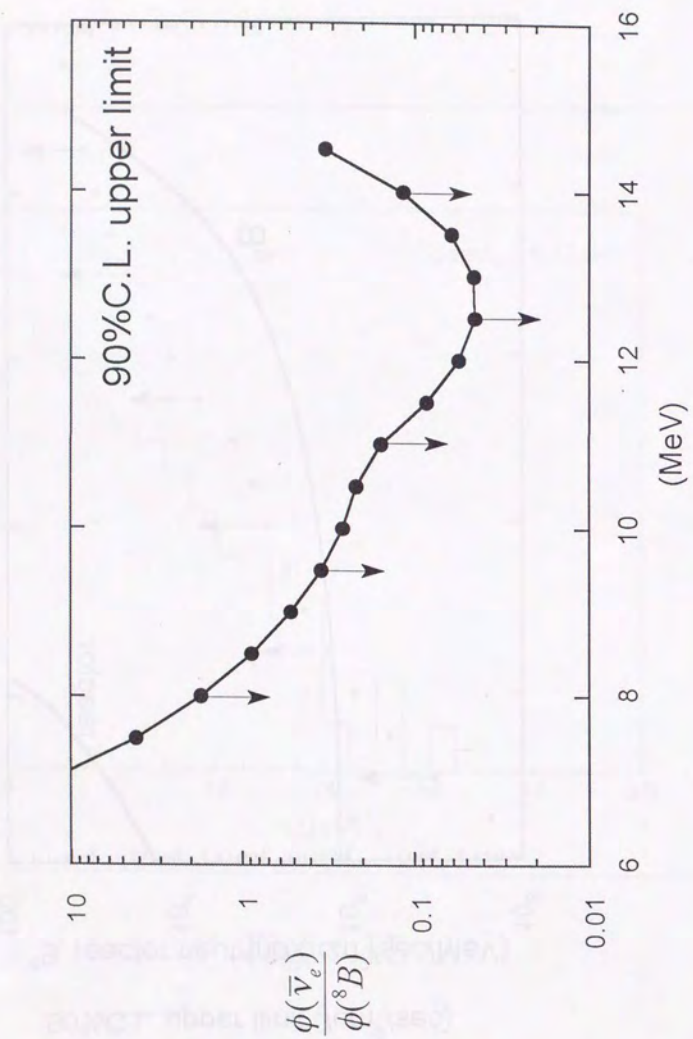
Fig. 7.1

Fig. 7.2

Fig. 7.3

Fig. 7.4

Fig. 7.5

$(\delta m^2, \sin^2 2\vartheta) = (10^{-5.2}, 10^{-2.2})$

$(\delta m^2, \sin^2 2\vartheta) = (10^{-5.4}, 10^{-0.2})$

Fig. 7.6

Fig. 7.7

Kamioka 90%C.L.

Fig. 7.8

Kamioka 90%C.L.

Fig. 7.9

Chlorine 90%C.L.

Fig. 7.10

Gallium 90%C.L.
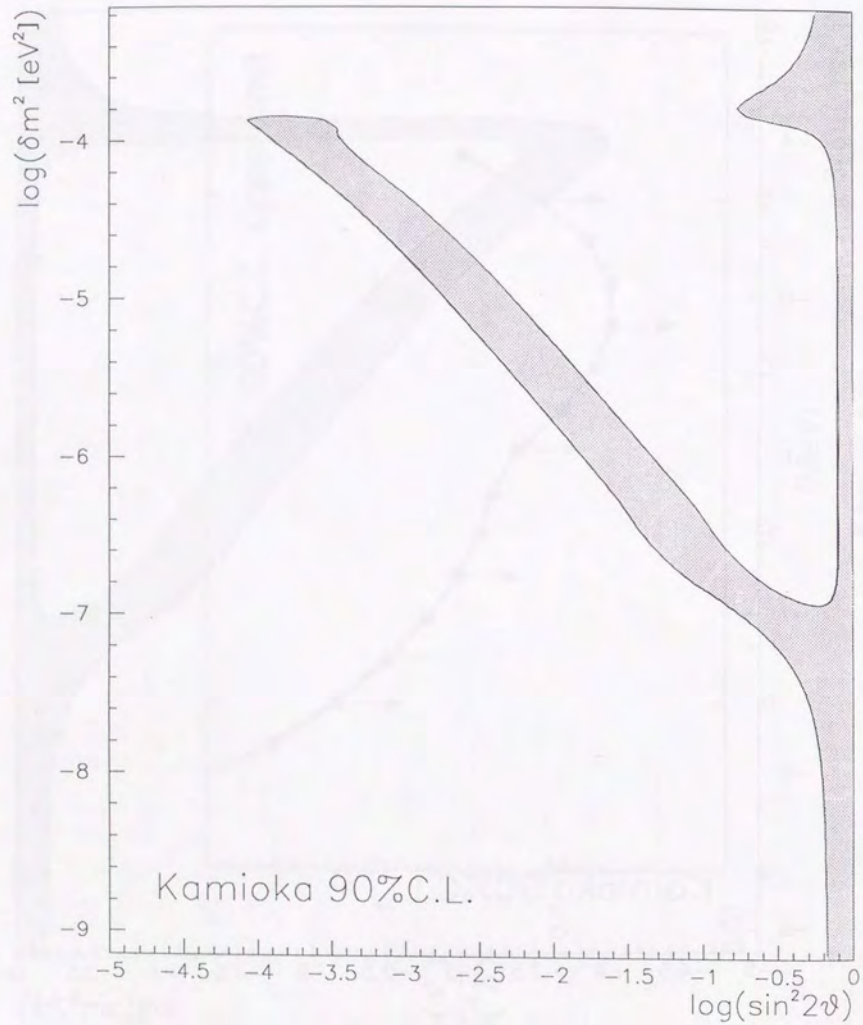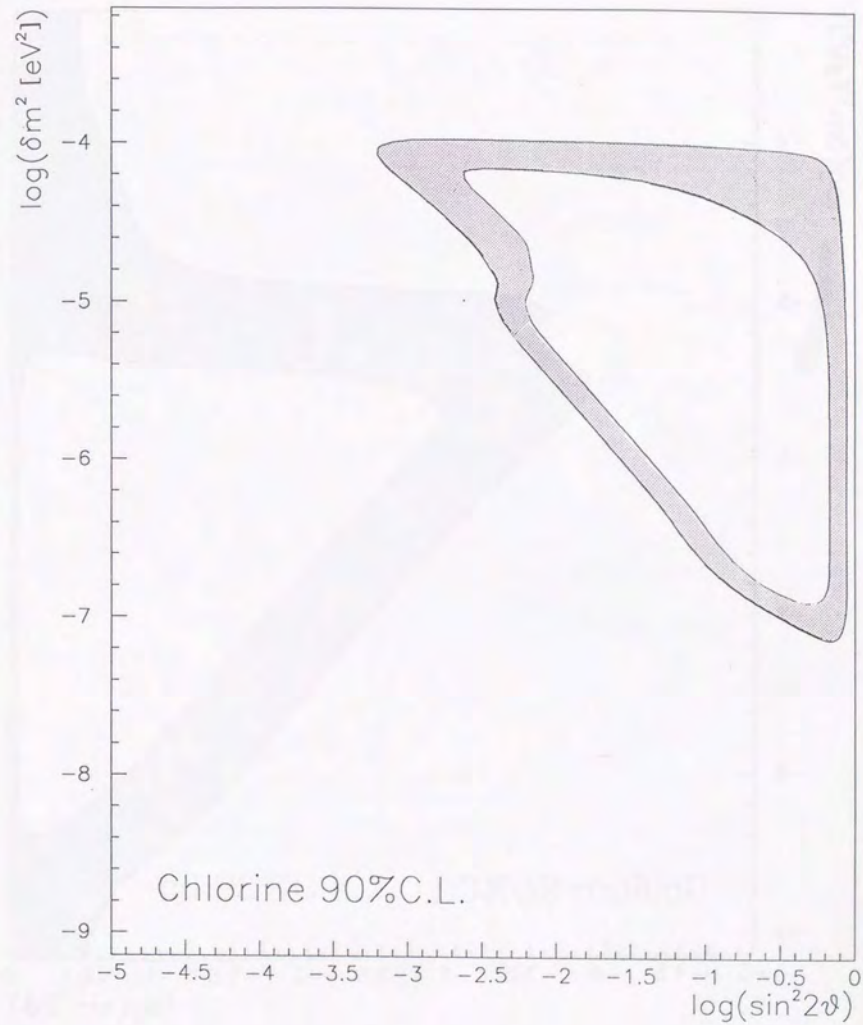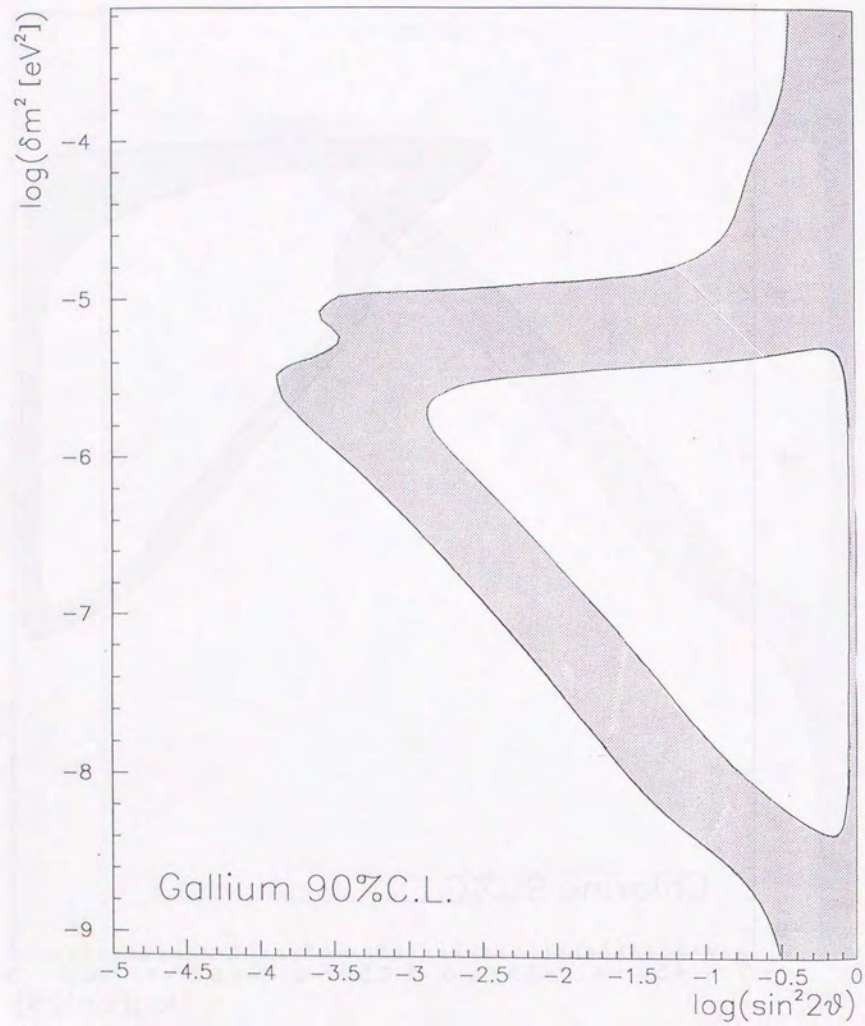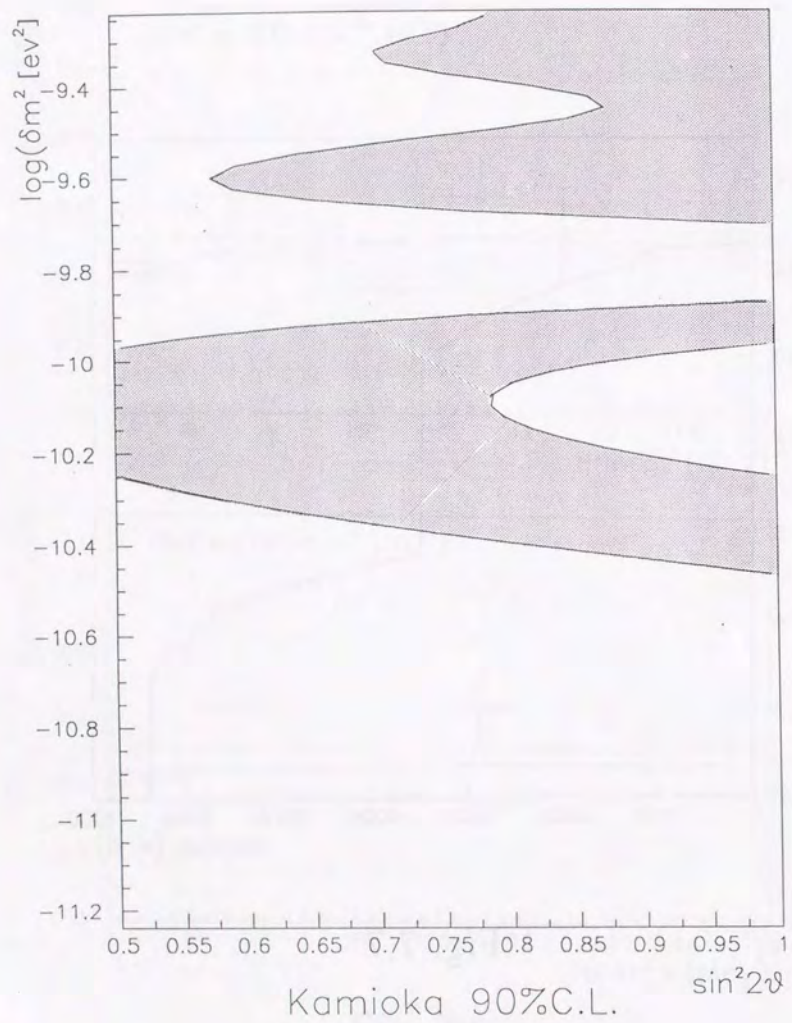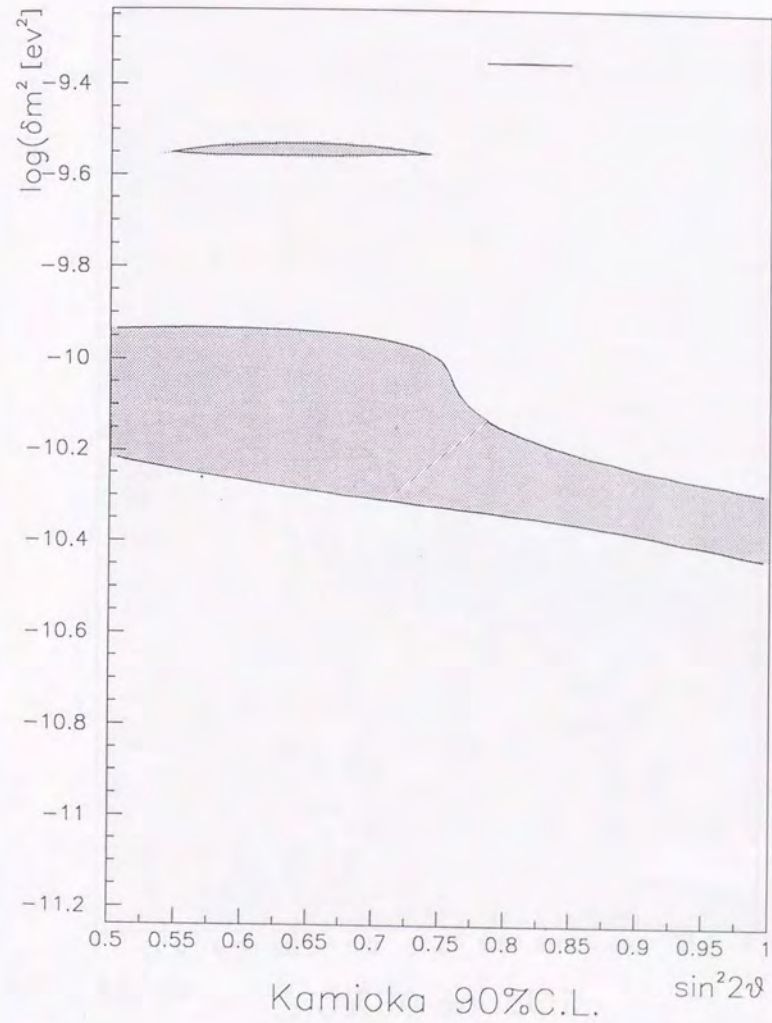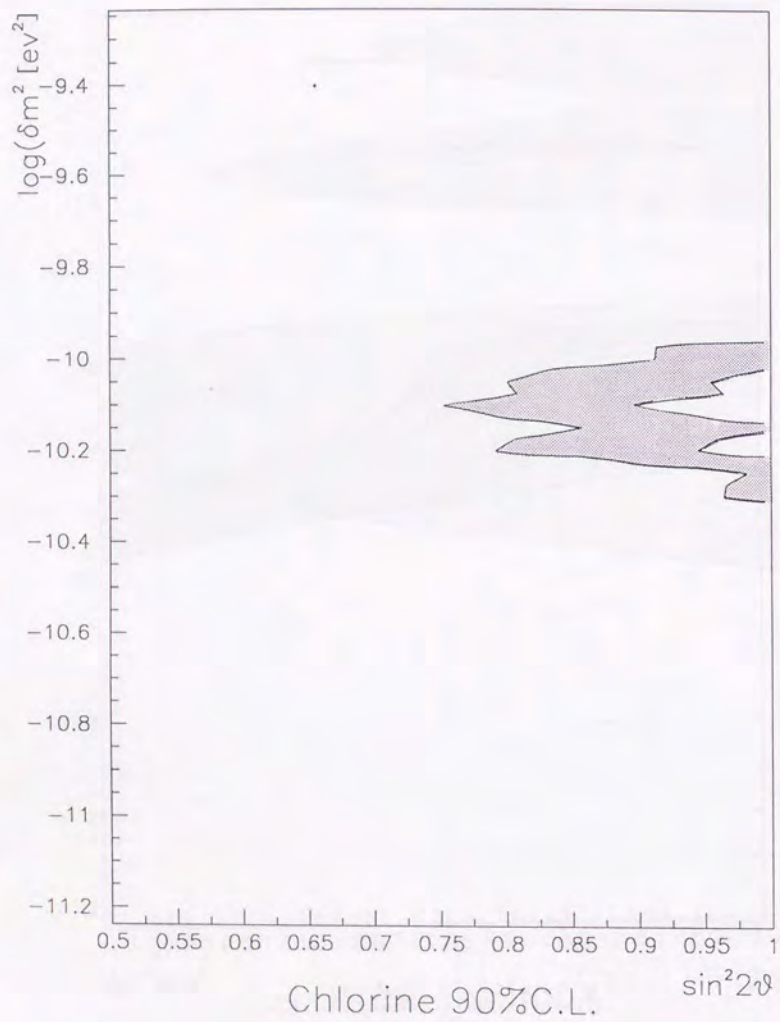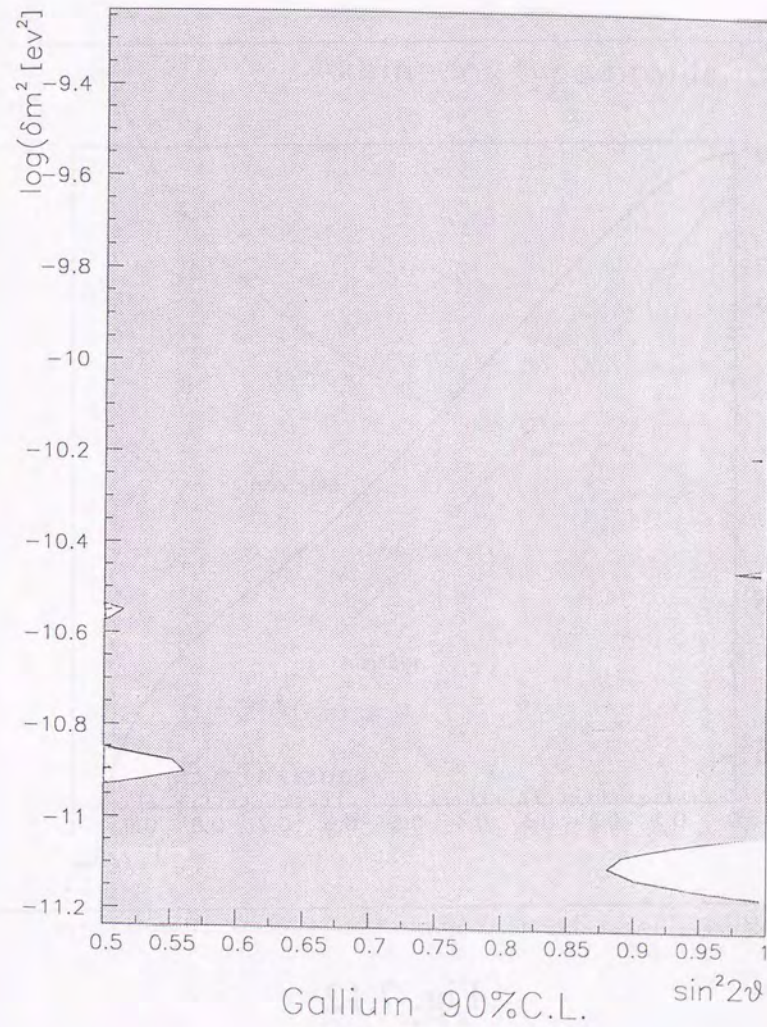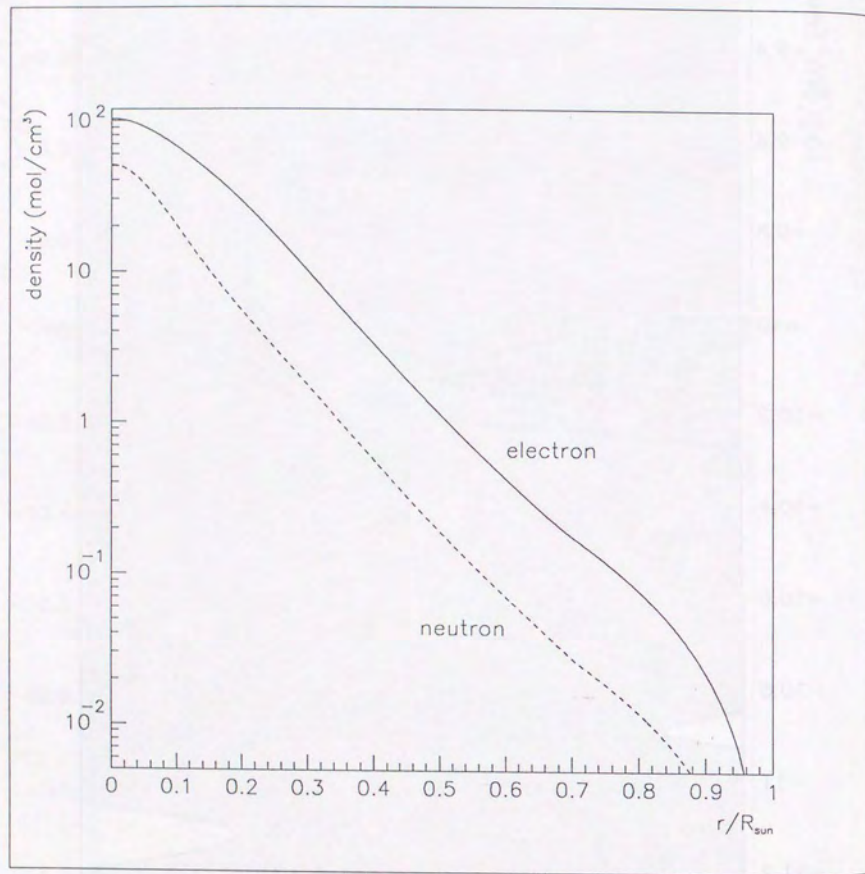
Fig. 7.11

Fig. 7.12

Fig. 7.13

Fig. 7.14

Fig. 7.15

Akhmedov type $B_0 = B_1 = 20\text{kG}$

$(\delta m^2, \sin^2 2\vartheta) = (7 \times 10^{-8}\,\text{eV}^2, 0.3)$

ν_e
ν_μ
$\bar{\nu}_e$
$\bar{\nu}_\mu$

r/R_{sun}

$B = 0\text{G}$

$(\delta m^2, \sin^2 2\vartheta) = (7 \times 10^{-8}\,\text{eV}^2, 0.3)$

ν_e
ν_μ
$\bar{\nu}_e$
$\bar{\nu}_\mu$

r/R_{sun}

Fig. 7.15 cont.

Akhmedov type $(B_0, B_1) = (20\text{kG}, 3\text{MG})$

$(\delta m^2, \sin^2 2\vartheta) = (10^{-5}\,\text{eV}^2, 0.2)$

ν_e
ν_μ
$\bar{\nu}_e$
$\bar{\nu}_\mu$

r/R_{sun}

Akhmedov type $(B_0, B_1) = (50\text{kG}, 1\text{MG})$

$(\delta m^2, \sin^2 2\vartheta) = (4 \times 10^{-7}\,\text{eV}^2, 1)$

ν_e
ν_μ
$\bar{\nu}_e$
$\bar{\nu}_\mu$

r/R_{sun}

Fig. 7.15 cont.

$B_1 = 1 MGauss$

$B_0 = 1k$

$B_0 = 2k$

$B_0 = 5k$

$B_0 = 10k$

$B_0 = 20k$

$B_0 = 25k$

$B_0 = 30k$

$B_0 = 35k$

$B_0 = 40k$

$B_0 = 45k$

$B_0 = 50k$

$B_0 = 60k$

Chlorine

Fig. 7.16

$B_1 = 3 MGauss$

$B_0 = 1k$

$B_0 = 2k$

$B_0 = 5k$

$B_0 = 10k$

$B_0 = 20k$

$B_0 = 25k$

$B_0 = 30k$

$B_0 = 35k$

$B_0 = 40k$

$B_0 = 45k$

$B_0 = 50k$

$B_0 = 60k$
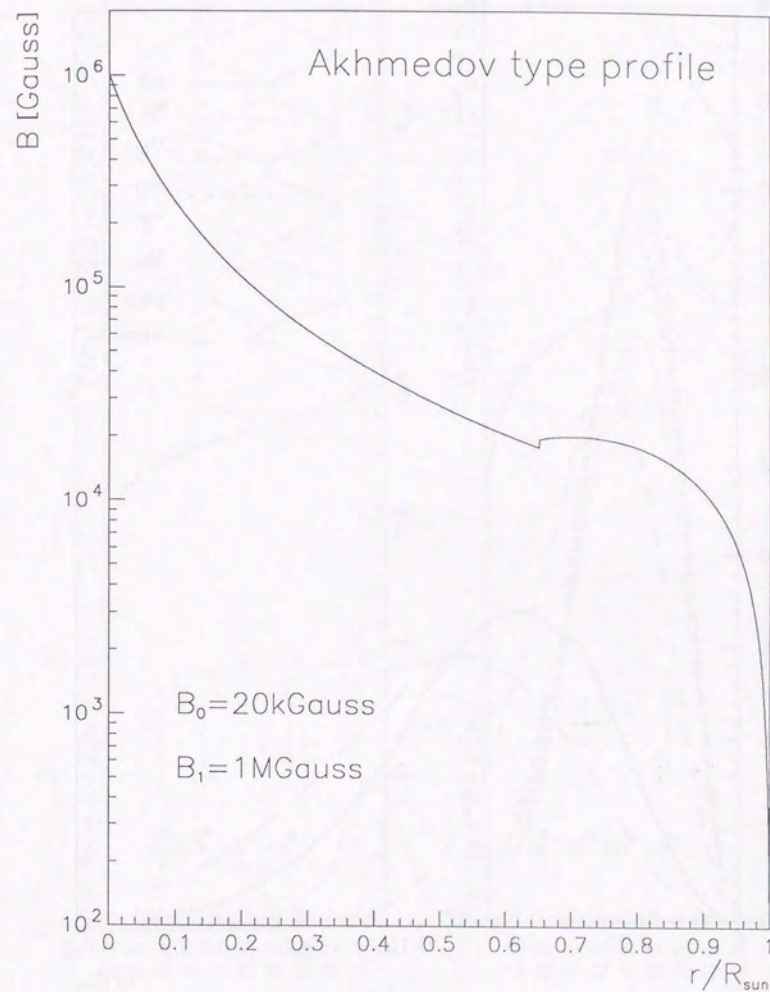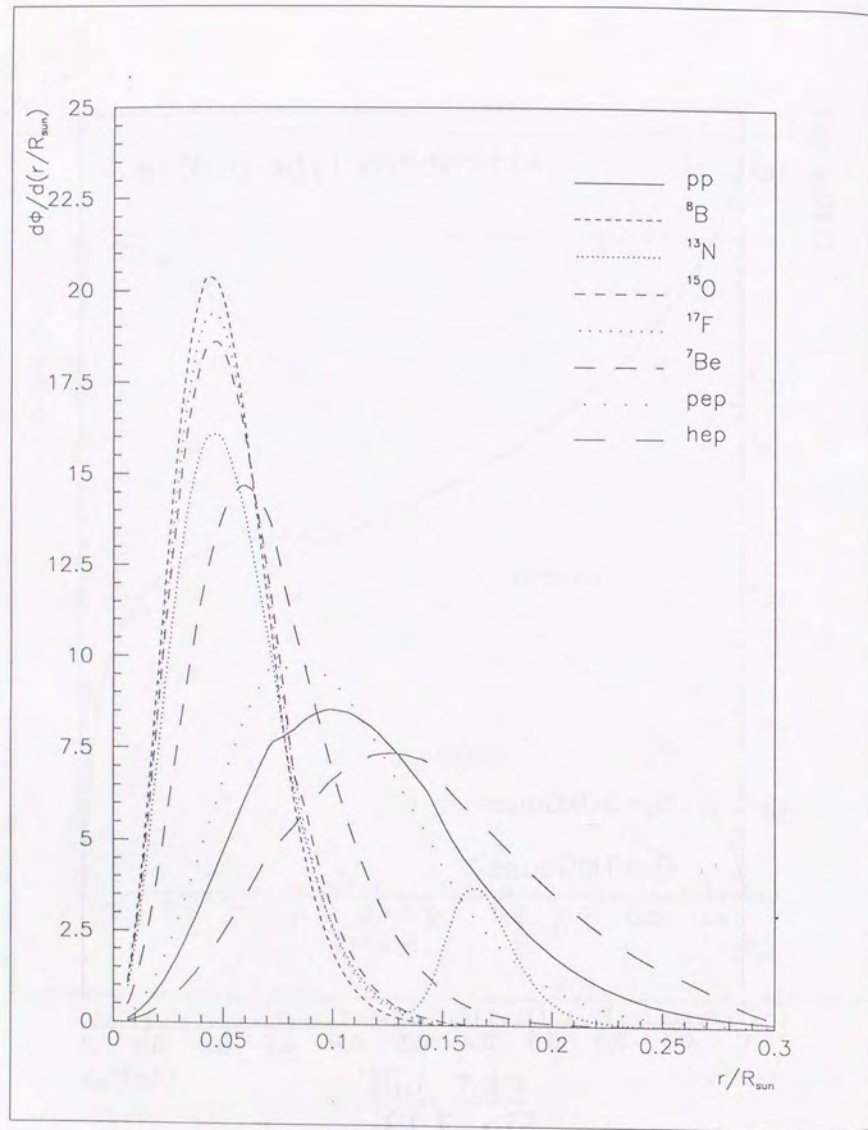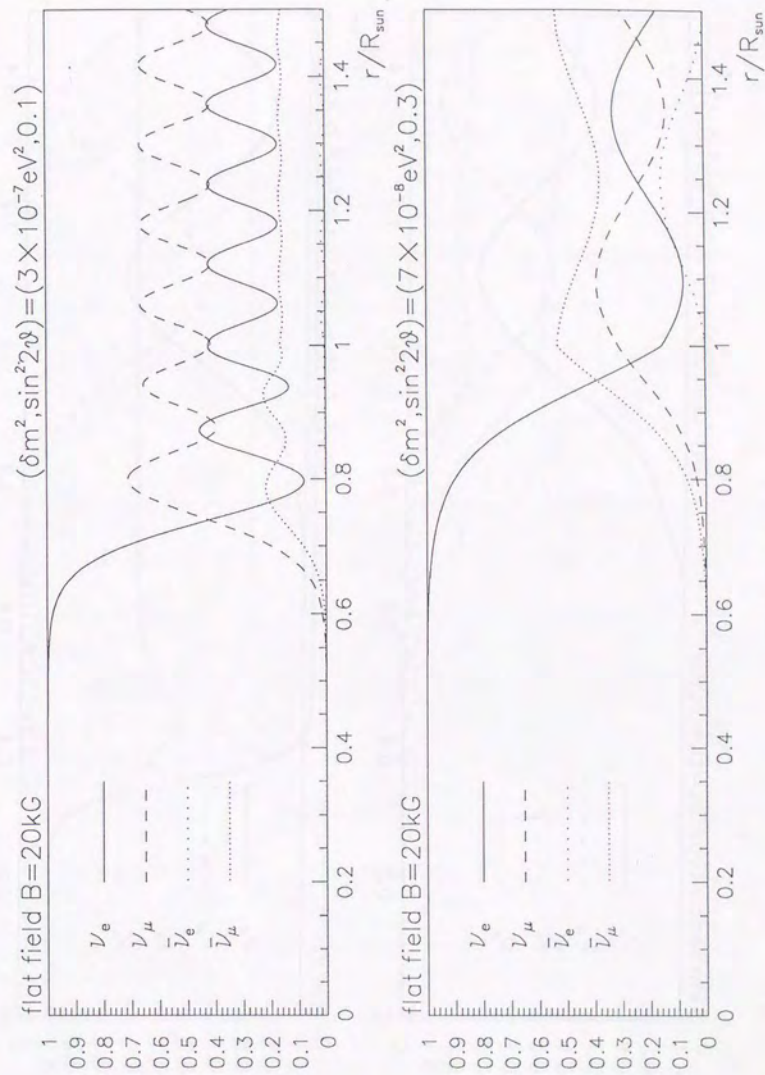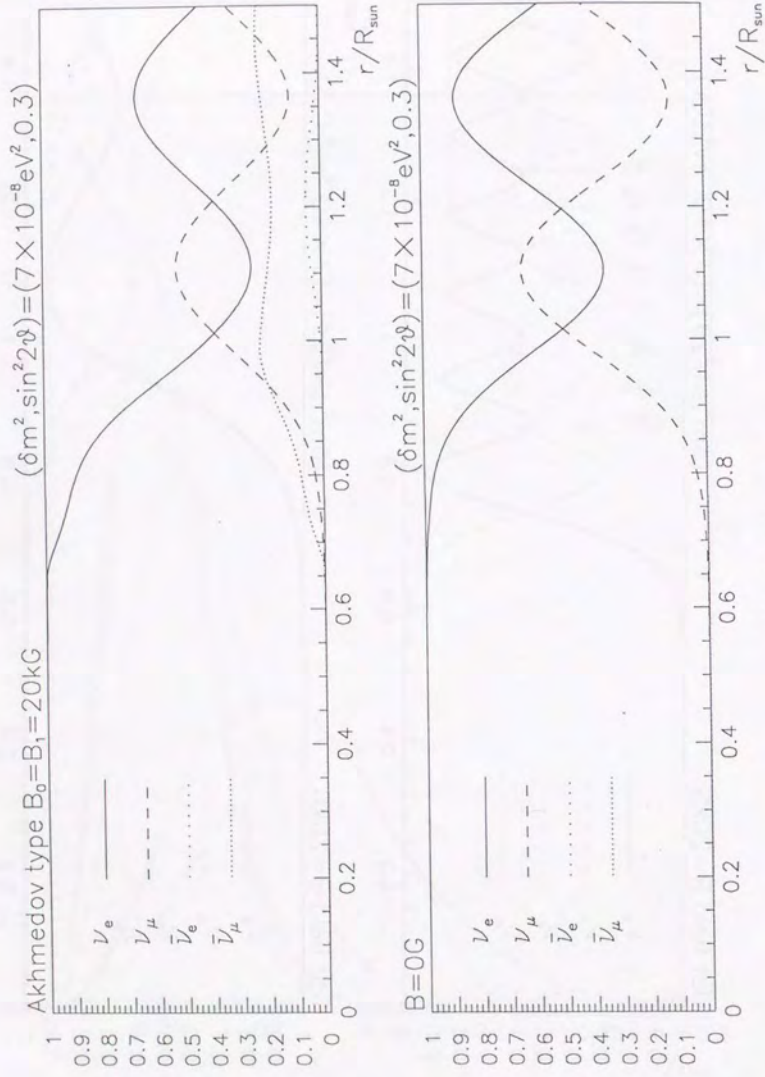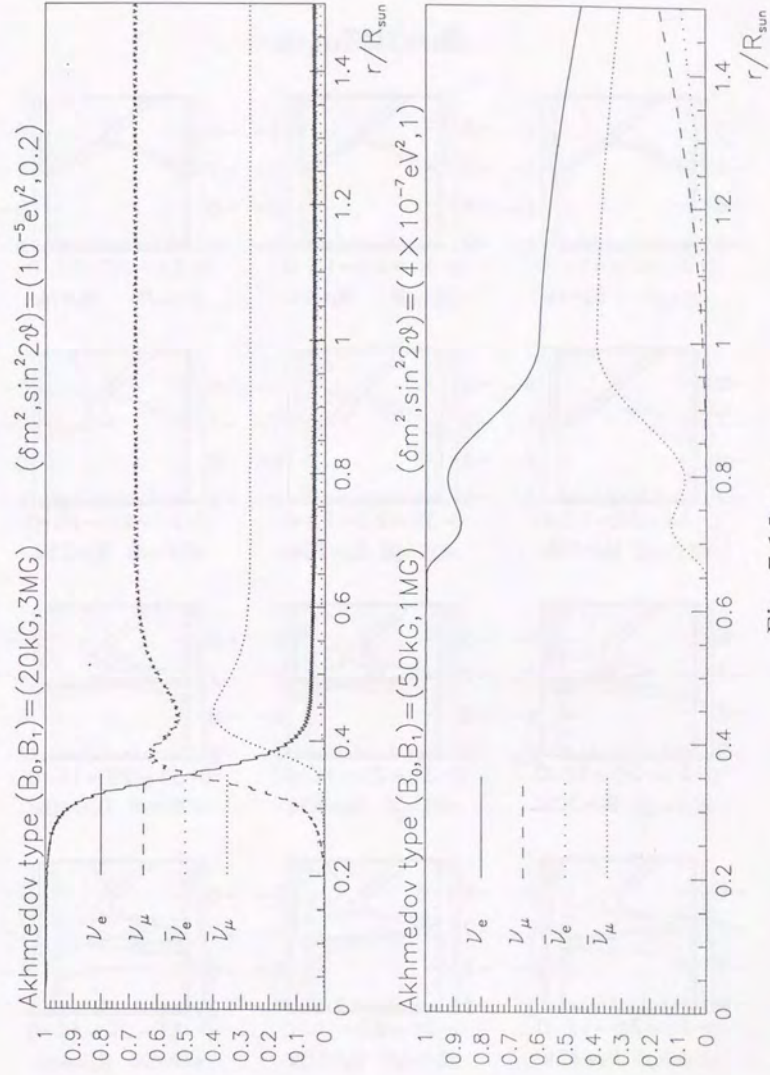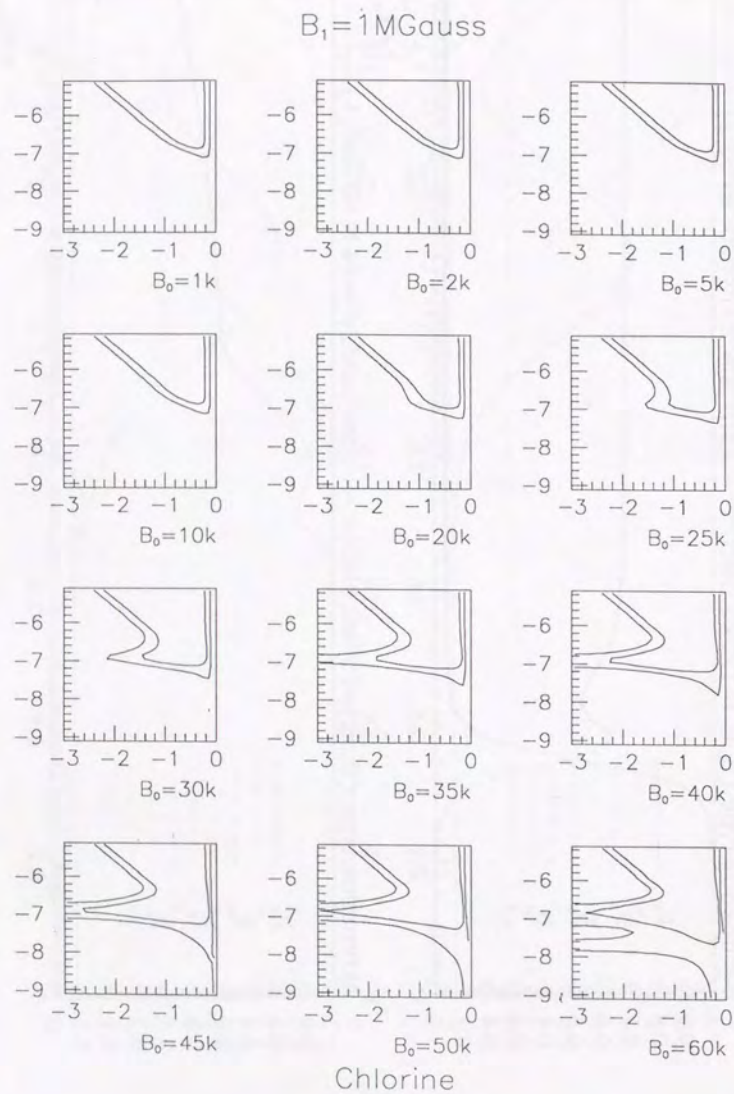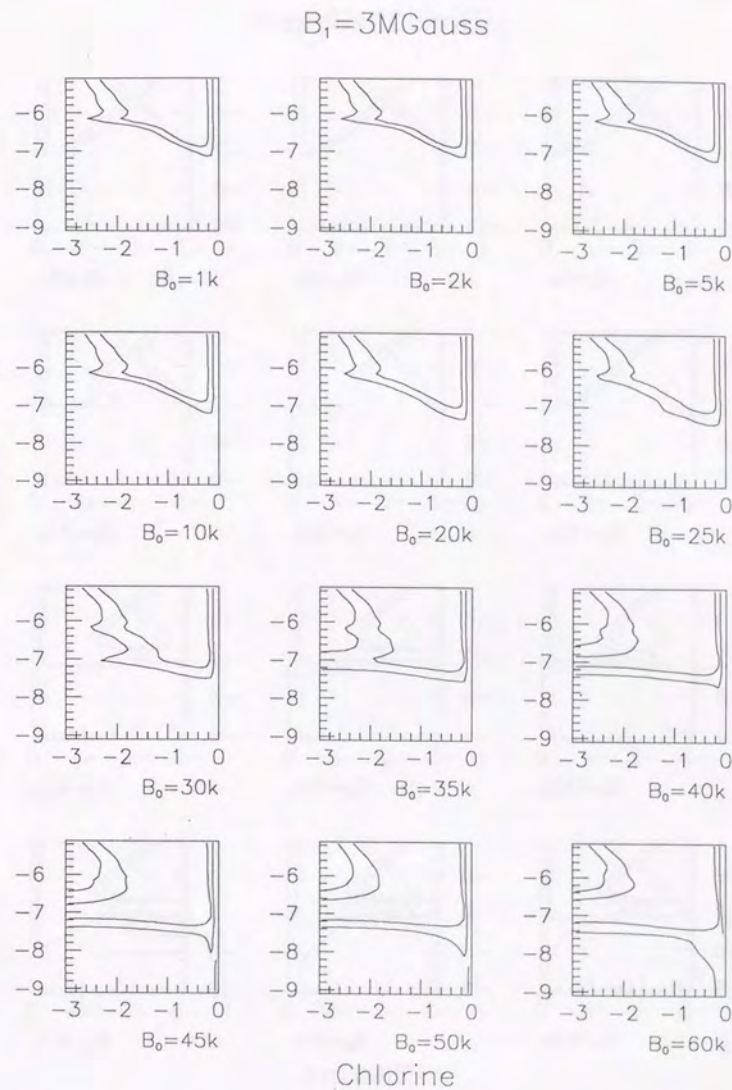
Chlorine

Fig. 7.16 cont.

$B_1 = 300\text{kGauss}$

$B_0 = 1\text{k}$

$B_0 = 2\text{k}$

$B_0 = 5\text{k}$

$B_0 = 10\text{k}$

$B_0 = 20\text{k}$

$B_0 = 25\text{k}$

$B_0 = 30\text{k}$

$B_0 = 35\text{k}$

$B_0 = 40\text{k}$

$B_0 = 45\text{k}$

$B_0 = 50\text{k}$

$B_0 = 60\text{k}$
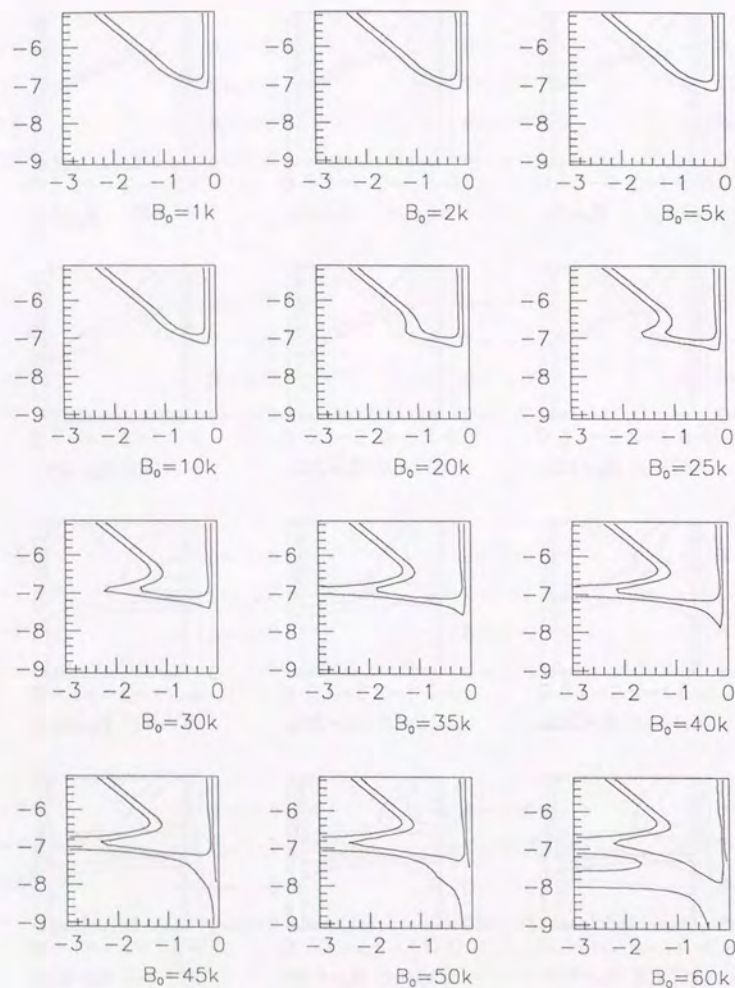
Chlorine

Fig. 7.16 cont.

$B_1 = 100\text{kGauss}$
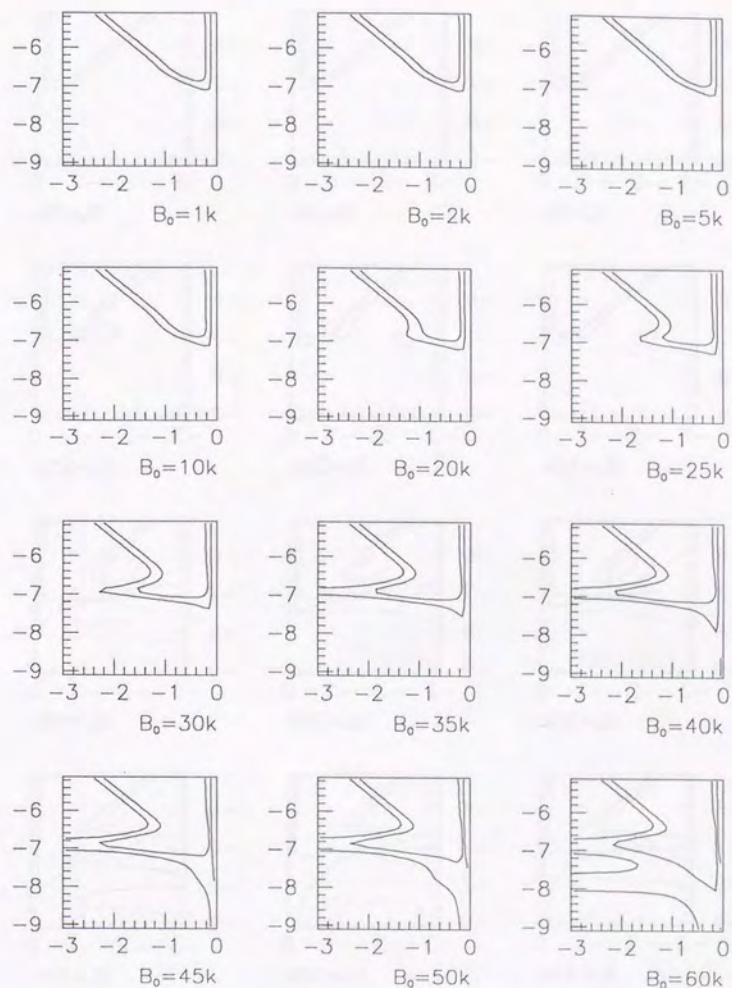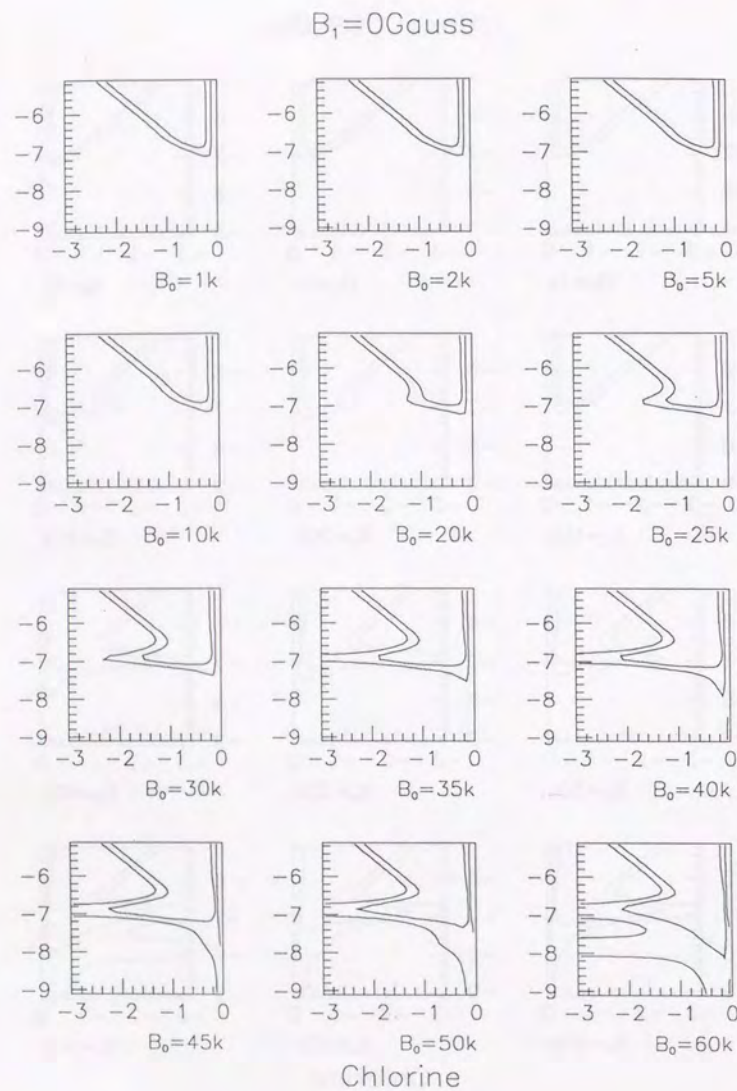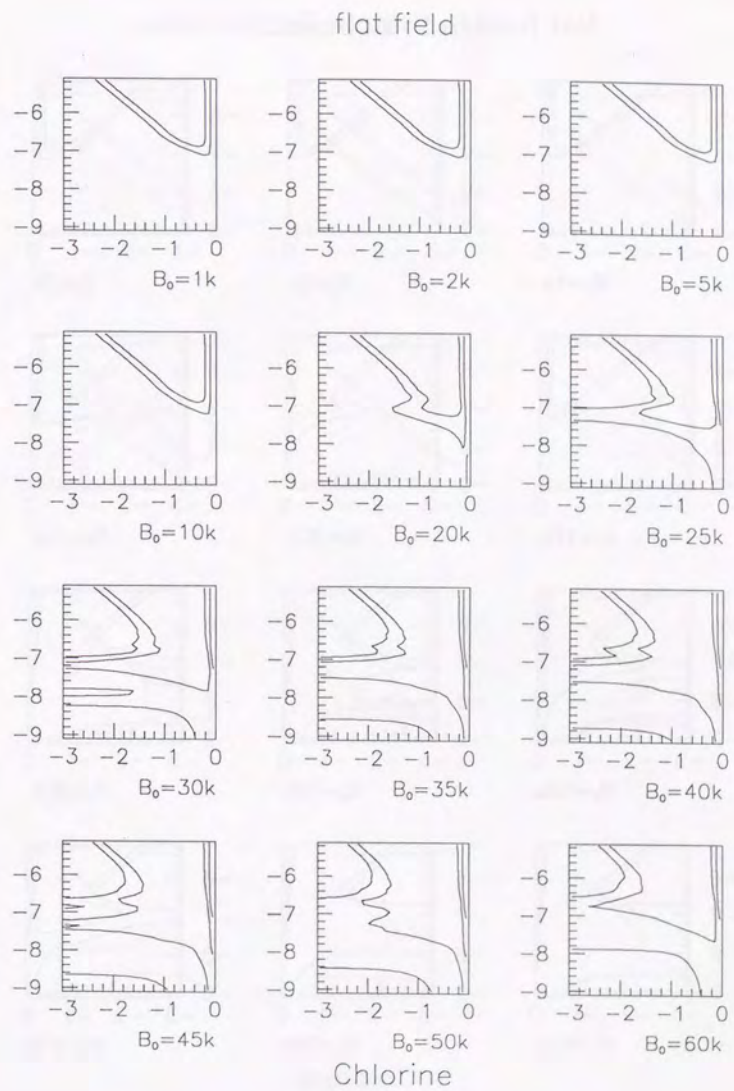
$B_0 = 1\text{k}$

$B_0 = 2\text{k}$

$B_0 = 5\text{k}$

$B_0 = 10\text{k}$

$B_0 = 20\text{k}$

$B_0 = 25\text{k}$

$B_0 = 30\text{k}$

$B_0 = 35\text{k}$

$B_0 = 40\text{k}$

$B_0 = 45\text{k}$

$B_0 = 50\text{k}$

$B_0 = 60\text{k}$

Chlorine

Fig. 7.16 cont.

$B_0 = 1k$ $B_0 = 2k$ $B_0 = 5k$

$B_0 = 10k$ $B_0 = 20k$ $B_0 = 25k$

$B_0 = 30k$ $B_0 = 35k$ $B_0 = 40k$

$B_0 = 45k$ $B_0 = 50k$ $B_0 = 60k$

Chlorine

Fig. 7.16 cont.

$B_0 = 1k$ $B_0 = 2k$ $B_0 = 5k$

$B_0 = 10k$ $B_0 = 20k$ $B_0 = 25k$

$B_0 = 30k$ $B_0 = 35k$ $B_0 = 40k$

$B_0 = 45k$ $B_0 = 50k$ $B_0 = 60k$

Chlorine

Fig. 7.16 cont.

Chlorine

Fig. 7.16 cont.

Gallium

Fig. 7.17

$B_1 = 3\text{MGauss}$

$B_0 = 1k$

$B_0 = 2k$

$B_0 = 5k$

$B_0 = 10k$

$B_0 = 20k$

$B_0 = 25k$

$B_0 = 30k$

$B_0 = 35k$

$B_0 = 40k$

$B_0 = 45k$

$B_0 = 50k$

$B_0 = 60k$
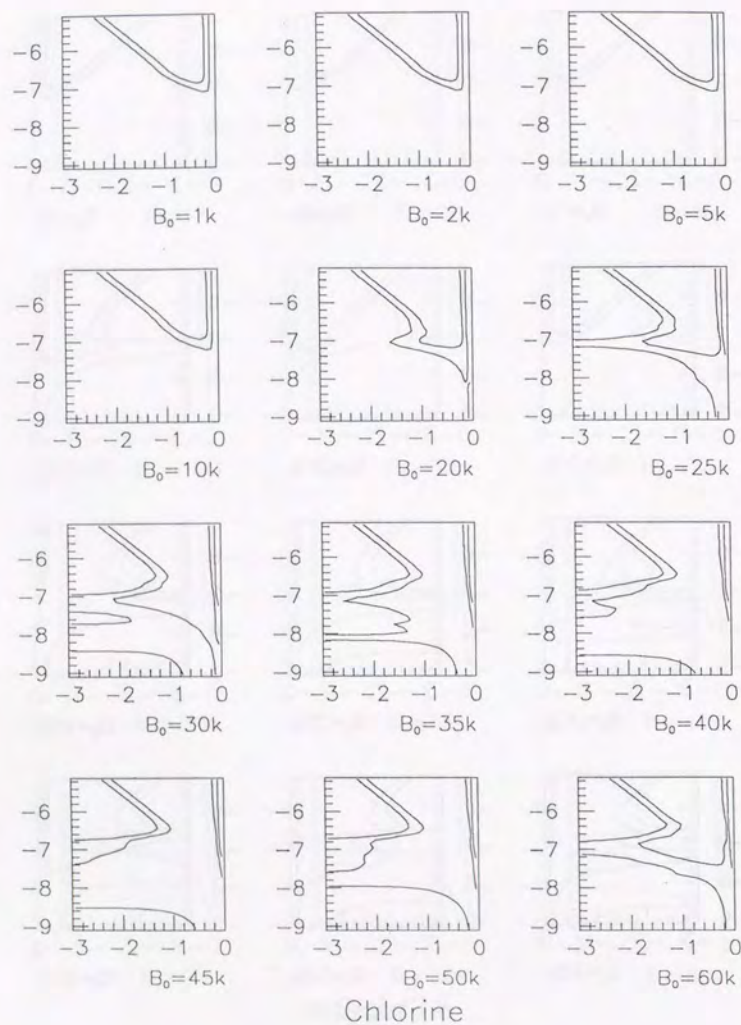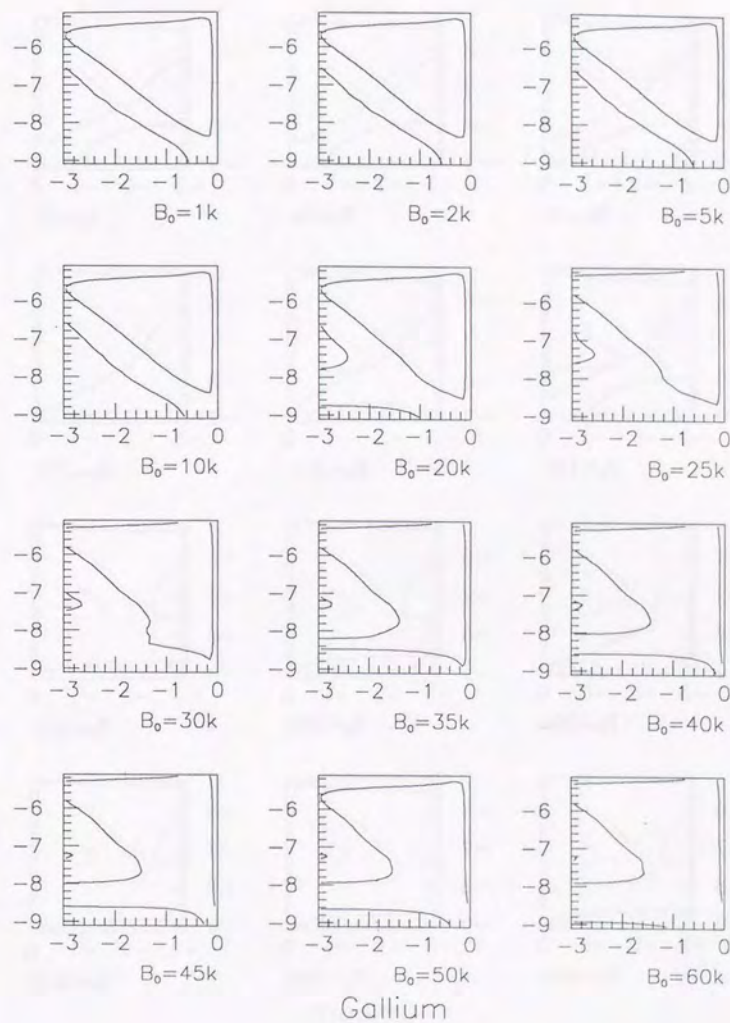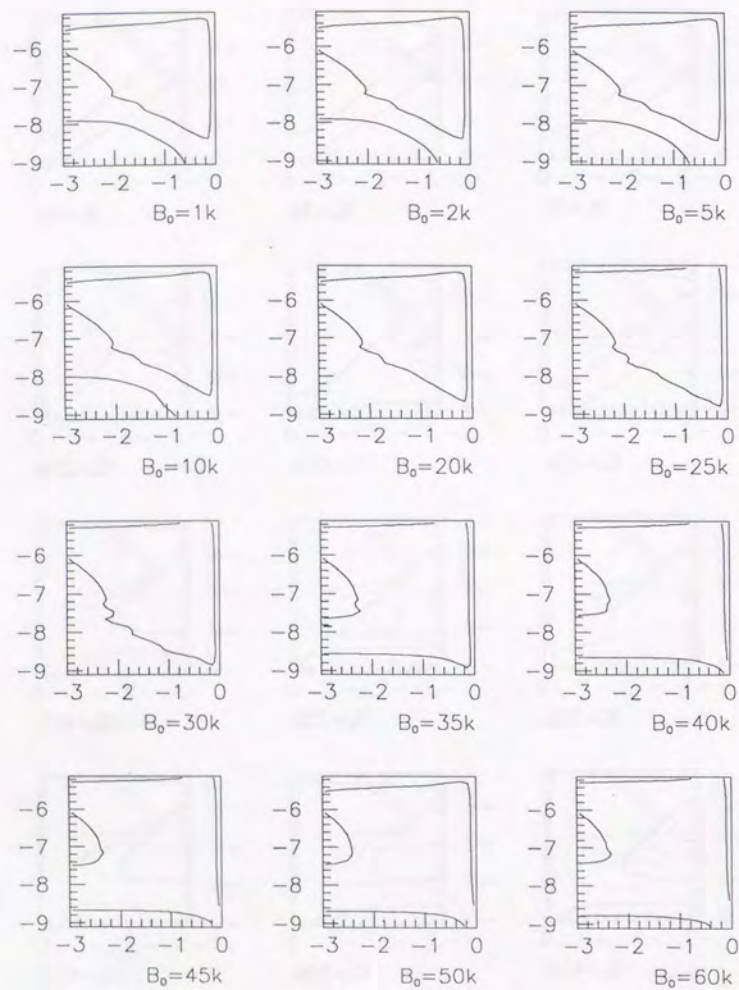
Gallium

Fig. 7.17 cont.

$B_1 = 300\text{kGauss}$

$B_0 = 1k$

$B_0 = 2k$

$B_0 = 5k$

$B_0 = 10k$

$B_0 = 20k$

$B_0 = 25k$

$B_0 = 30k$

$B_0 = 35k$

$B_0 = 40k$

$B_0 = 45k$

$B_0 = 50k$

$B_0 = 60k$
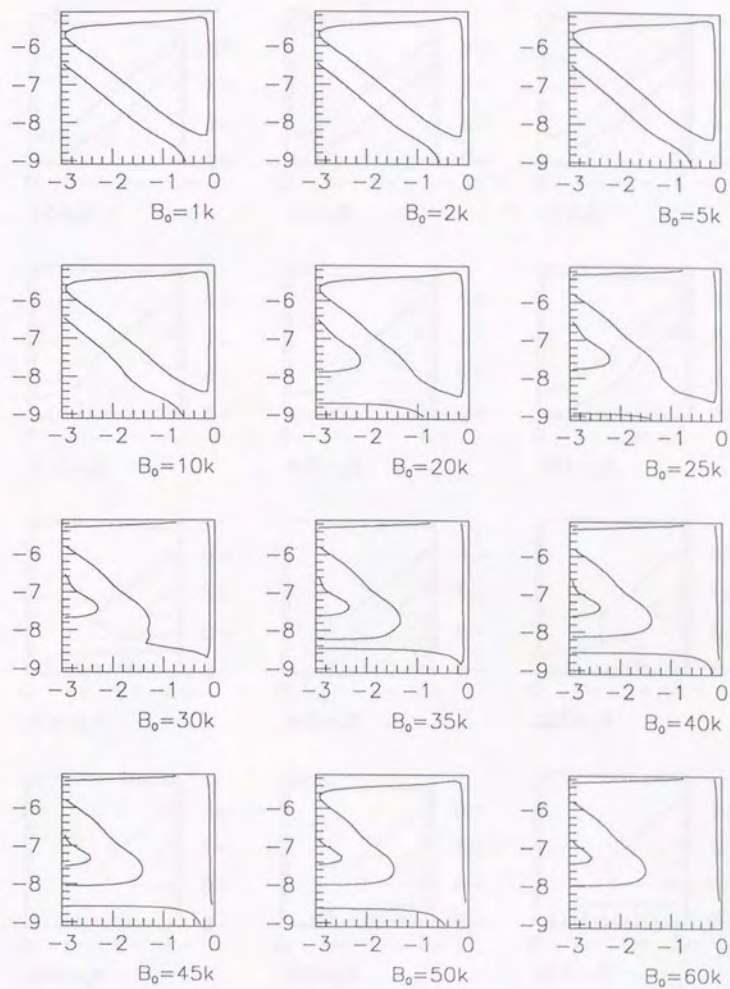
Gallium

Fig. 7.17 cont.

$B_1 = 100\text{kGauss}$

$B_0 = 1\text{k}$ $B_0 = 2\text{k}$ $B_0 = 5\text{k}$

$B_0 = 10\text{k}$ $B_0 = 20\text{k}$ $B_0 = 25\text{k}$

$B_0 = 30\text{k}$ $B_0 = 35\text{k}$ $B_0 = 40\text{k}$

$B_0 = 45\text{k}$ $B_0 = 50\text{k}$ $B_0 = 60\text{k}$
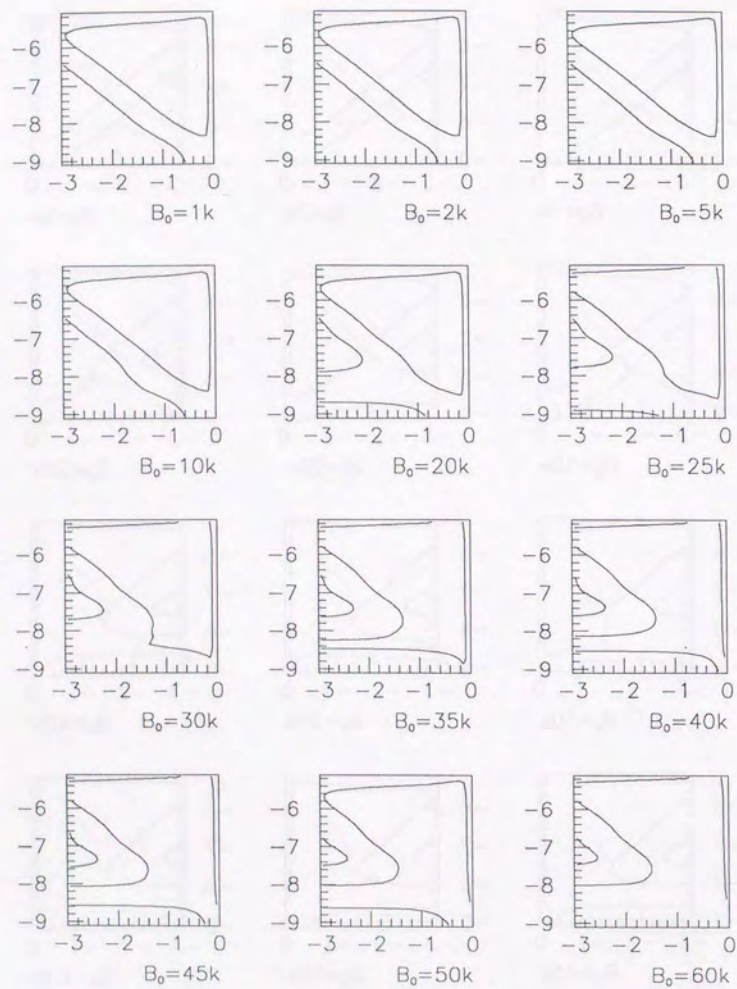
Gallium

Fig. 7.17 cont.

$B_1 = 0\text{Gauss}$

$B_0 = 1\text{k}$ $B_0 = 2\text{k}$ $B_0 = 5\text{k}$

$B_0 = 10\text{k}$ $B_0 = 20\text{k}$ $B_0 = 25\text{k}$

$B_0 = 30\text{k}$ $B_0 = 35\text{k}$ $B_0 = 40\text{k}$

$B_0 = 45\text{k}$ $B_0 = 50\text{k}$ $B_0 = 60\text{k}$
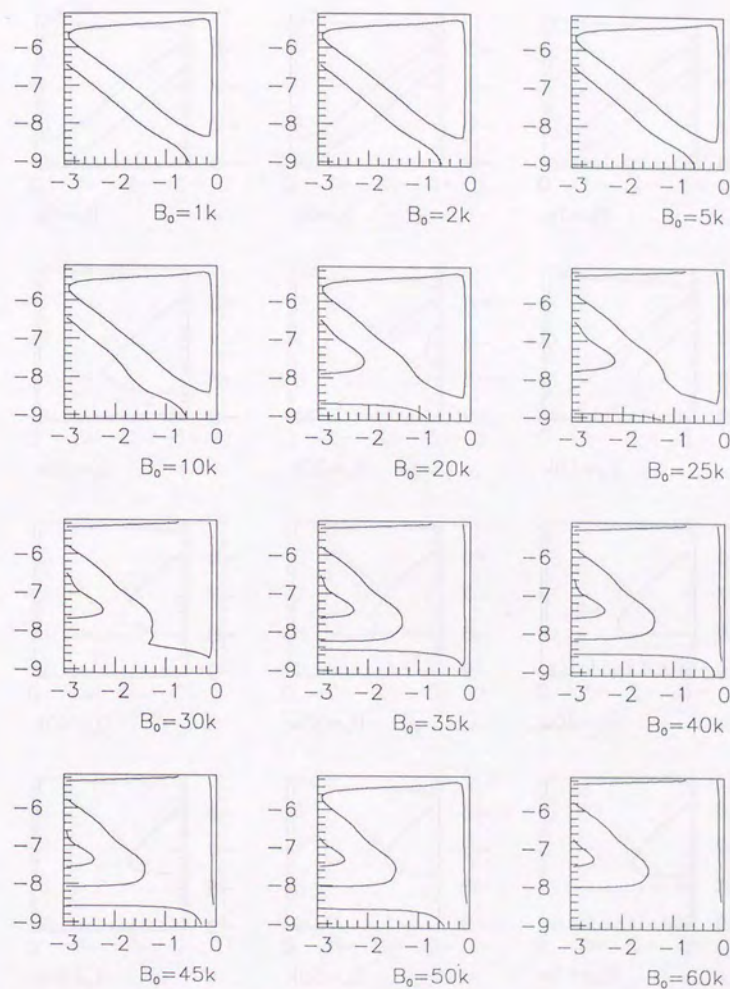
Gallium

Fig. 7.17 cont.

flat field
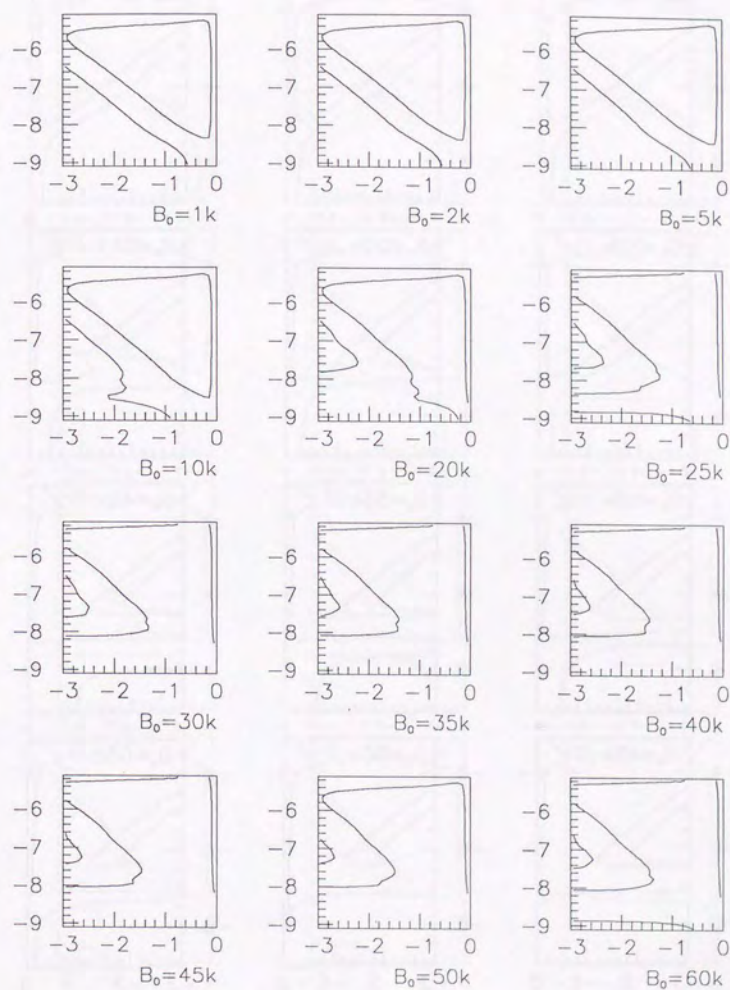
flat field in the convection zone

$B_0=1k$

$B_0=2k$

$B_0=5k$

$B_0=10k$

$B_0=20k$

$B_0=25k$

$B_0=30k$

$B_0=35k$

$B_0=40k$

$B_0=45k$

$B_0=50k$

$B_0=60k$

Gallium

Gallium

Fig. 7.17 cont.

Fig. 7.17 cont.

B₁=1MGauss

Kamioka

Fig. 7.18

B₁=3MGauss

Kamioka

Fig. 7.18 cont.

B₁=300kGauss

B₀=1k B₀=2k B₀=5k

B₀=10k B₀=20k B₀=25k

B₀=30k B₀=35k B₀=40k

B₀=45k B₀=50k B₀=60k

Kamioka

Fig. 7.18 cont.

B₁=100kGauss

B₀=1k B₀=2k B₀=5k

B₀=10k B₀=20k B₀=25k

B₀=30k B₀=35k B₀=40k

B₀=45k B₀=50k B₀=60k

Kamioka

Fig. 7.18 cont.

B₁=0Gauss
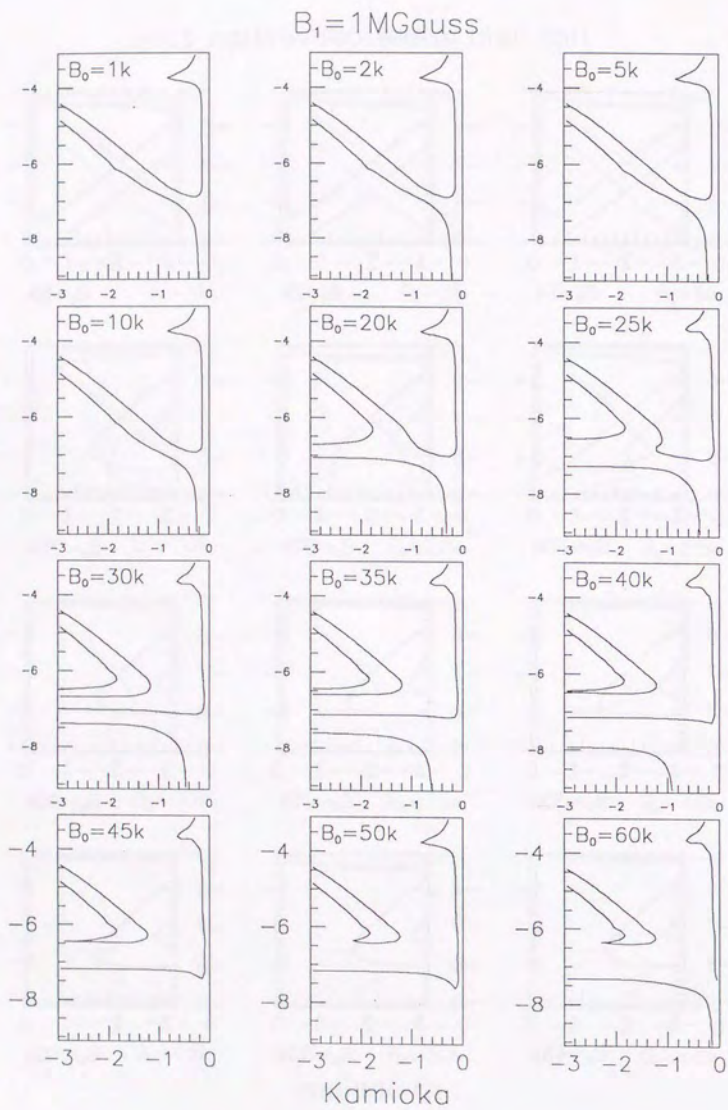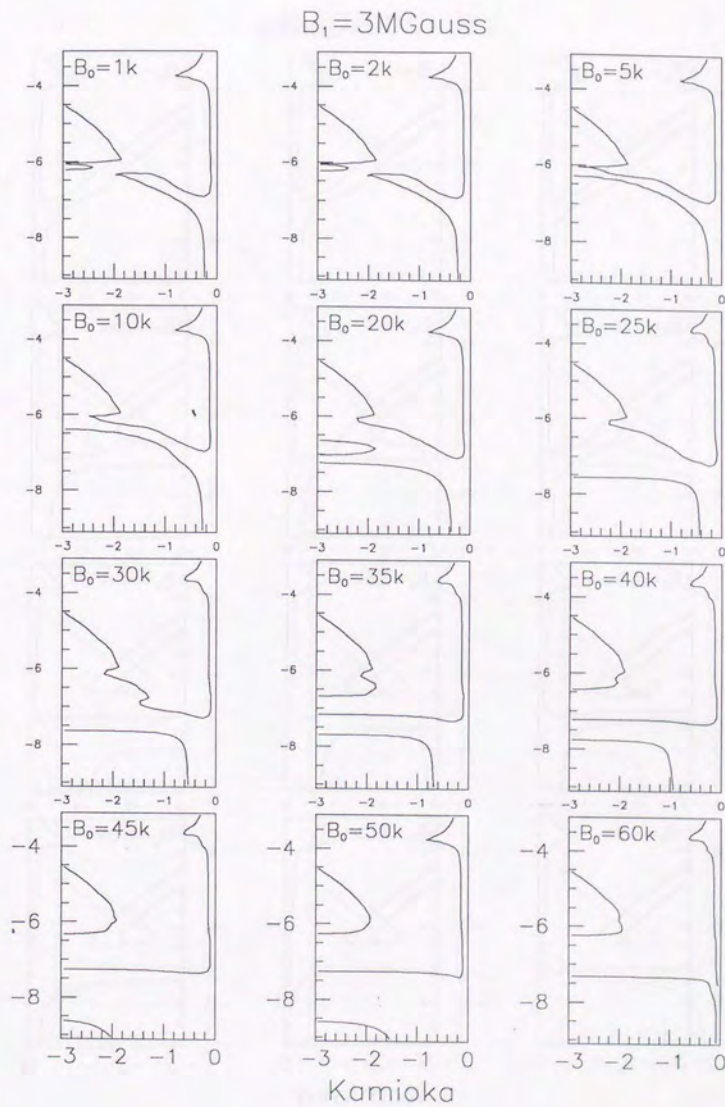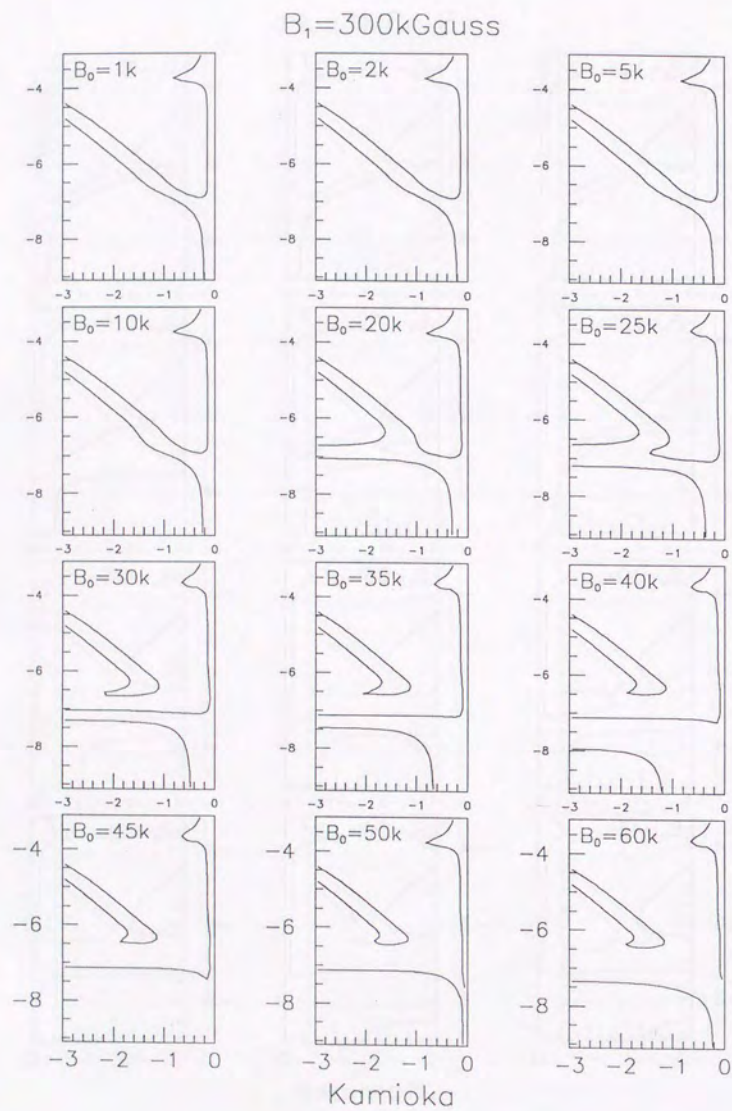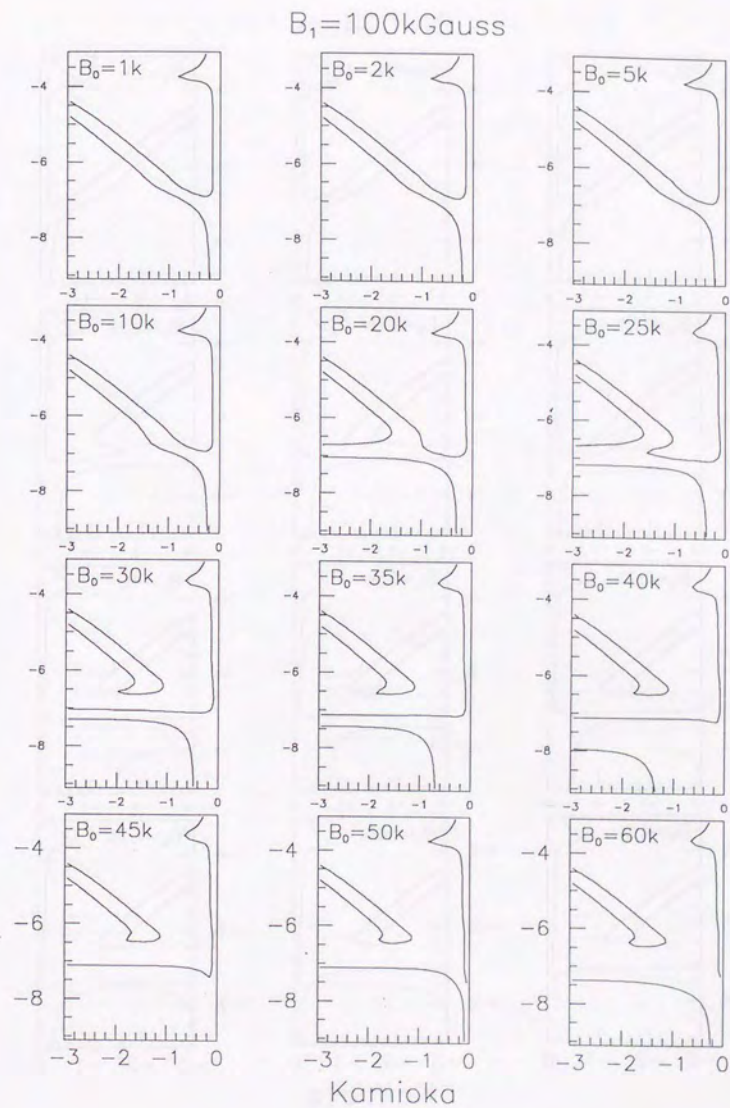
Kamioka
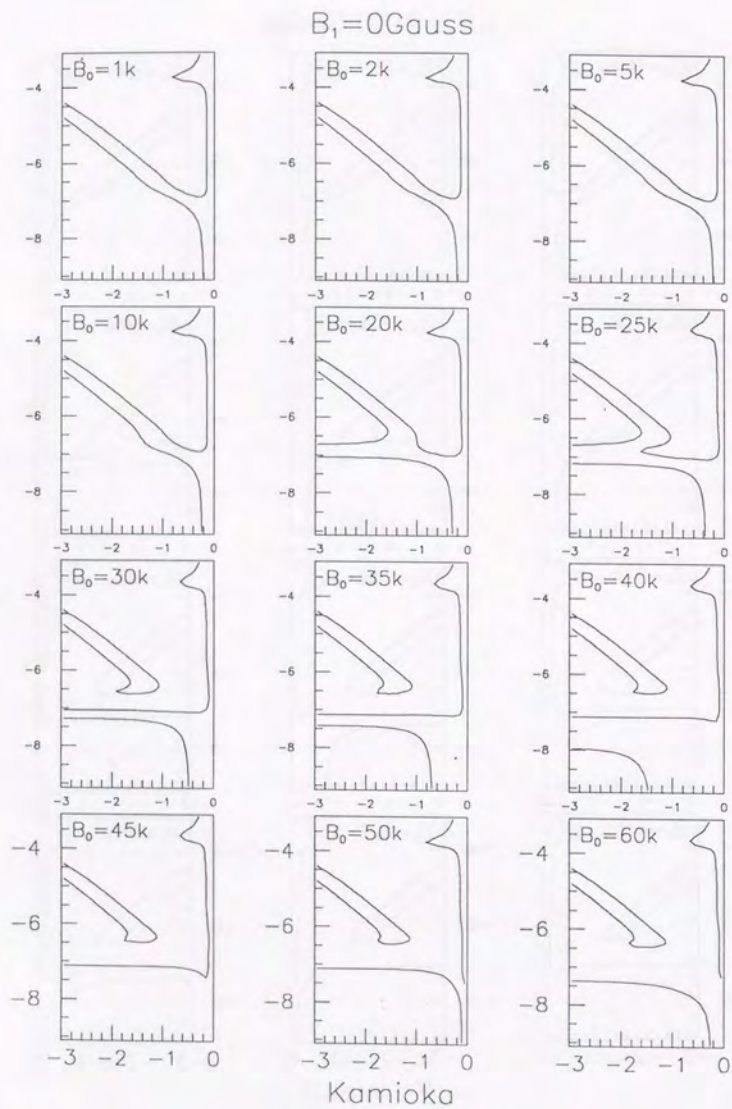
Fig. 7.18 cont.
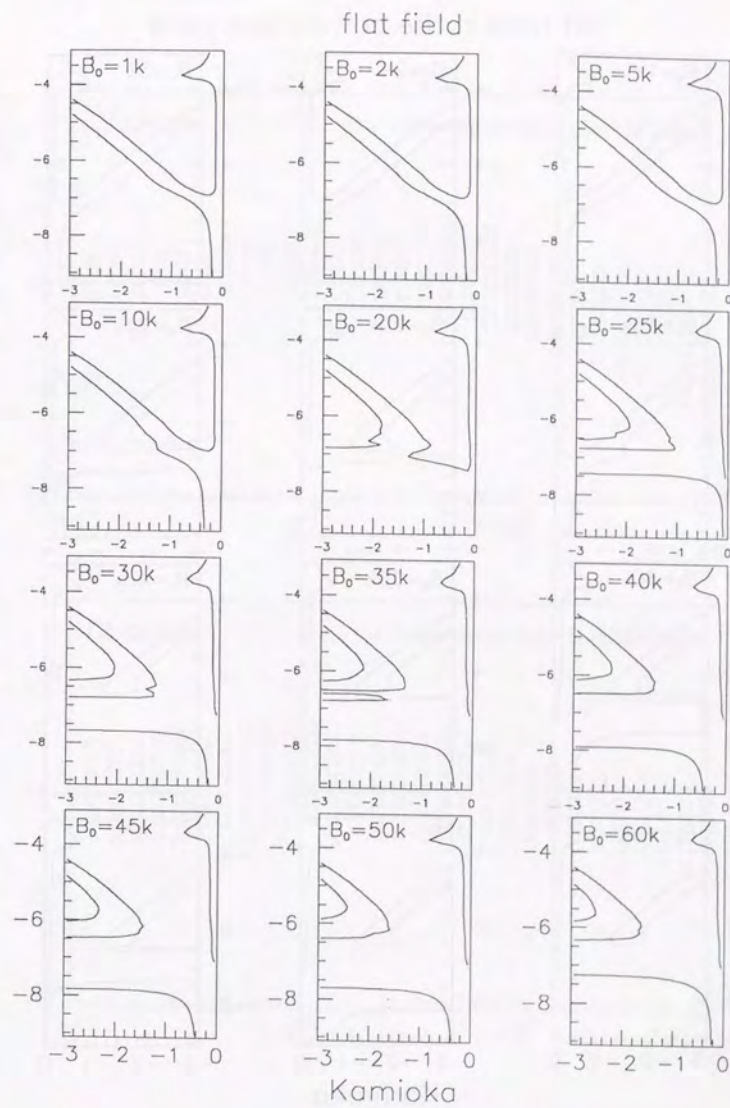
flat field
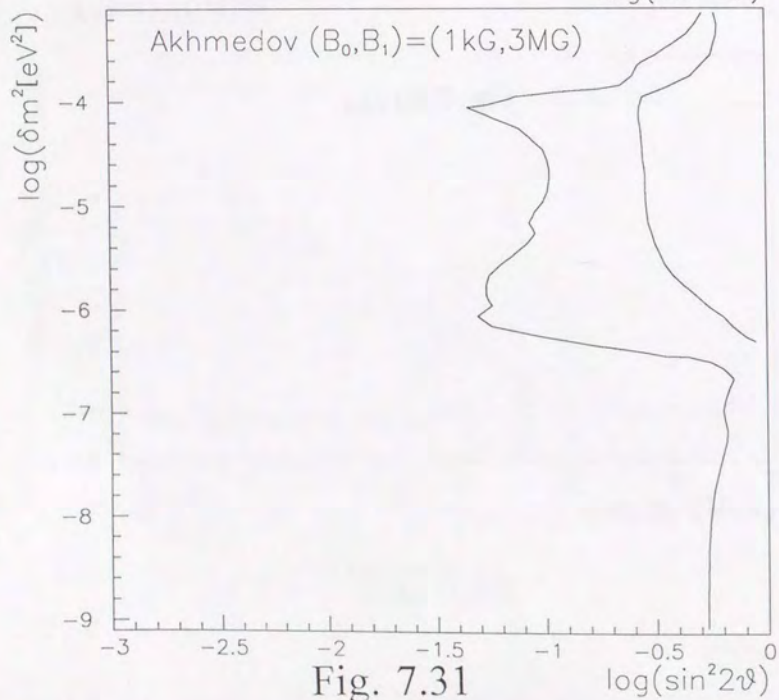
Kamioka
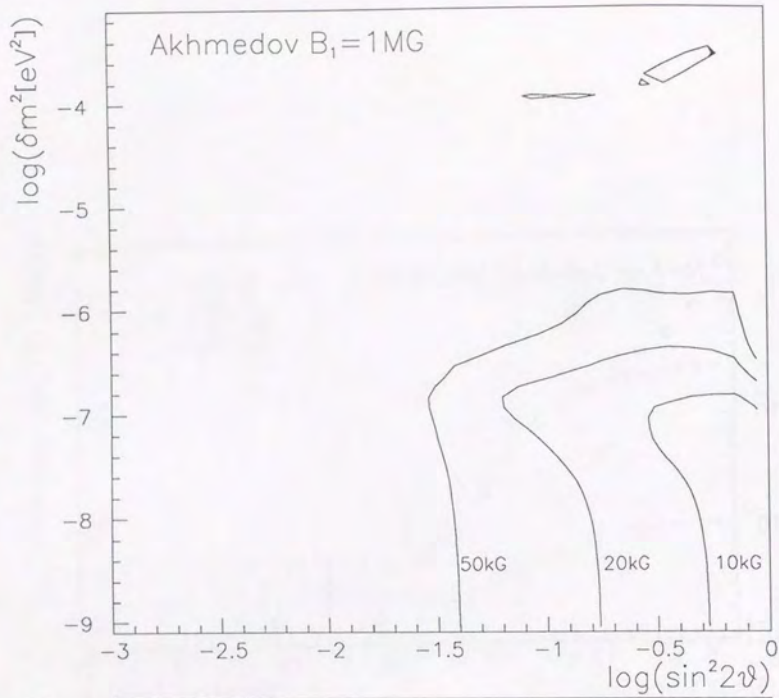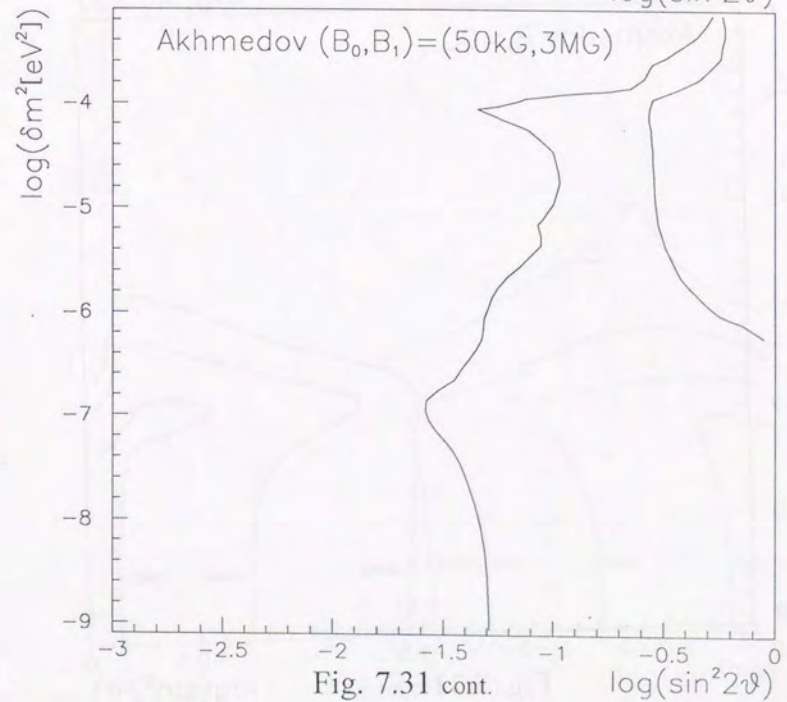
Fig. 7.18 cont.
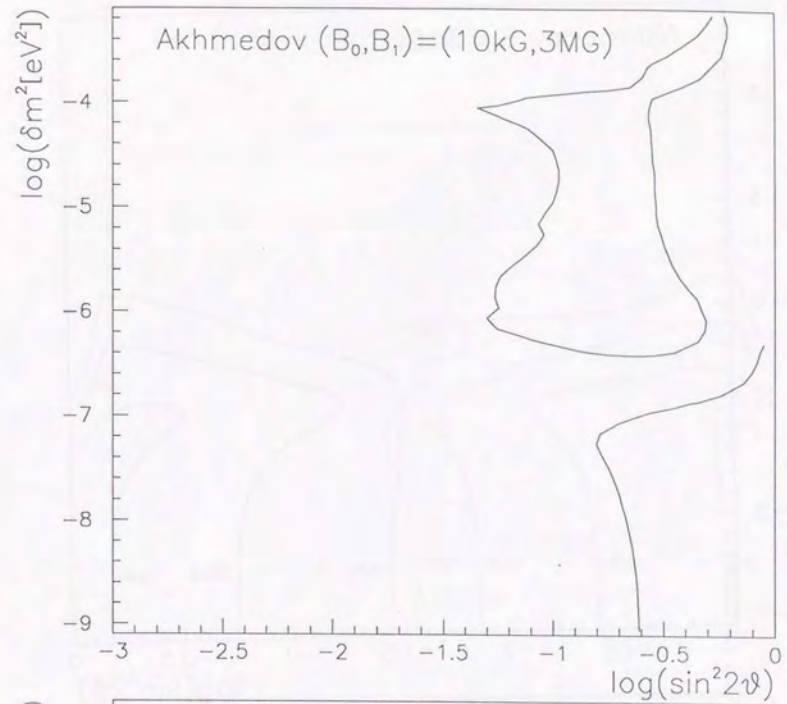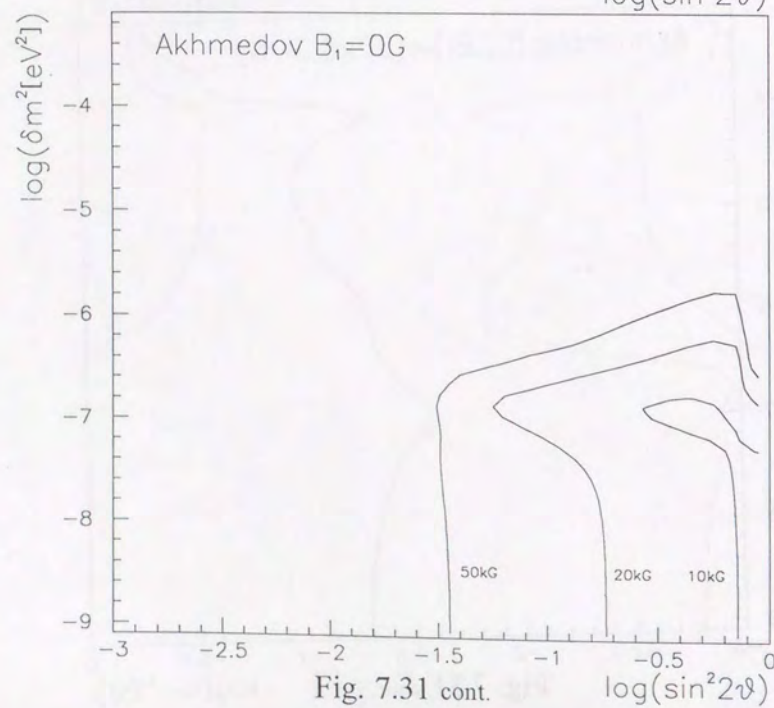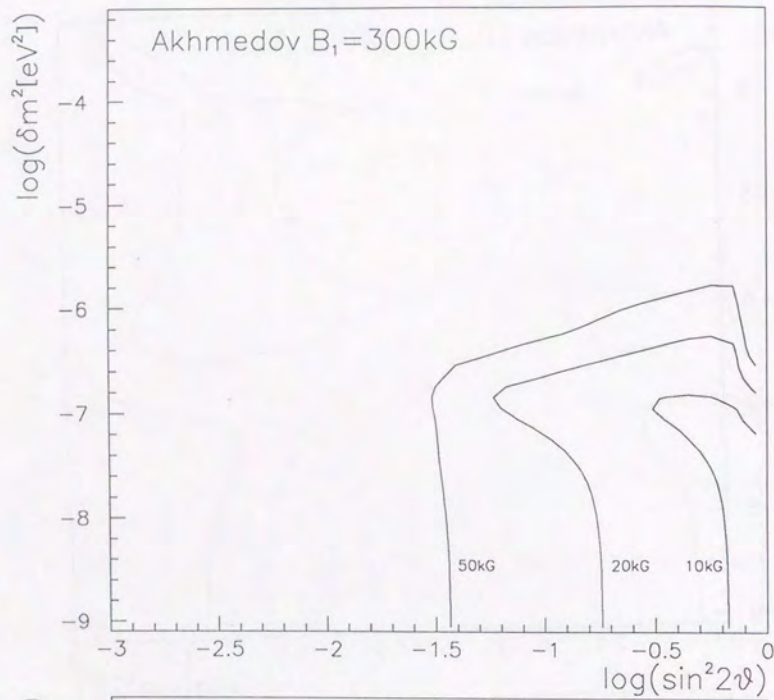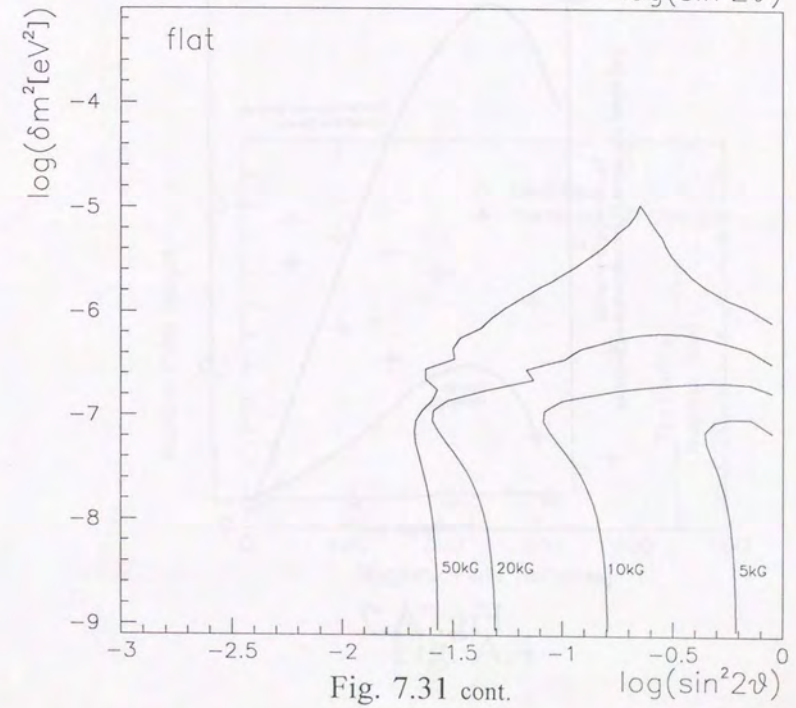
flat field in the convection zone
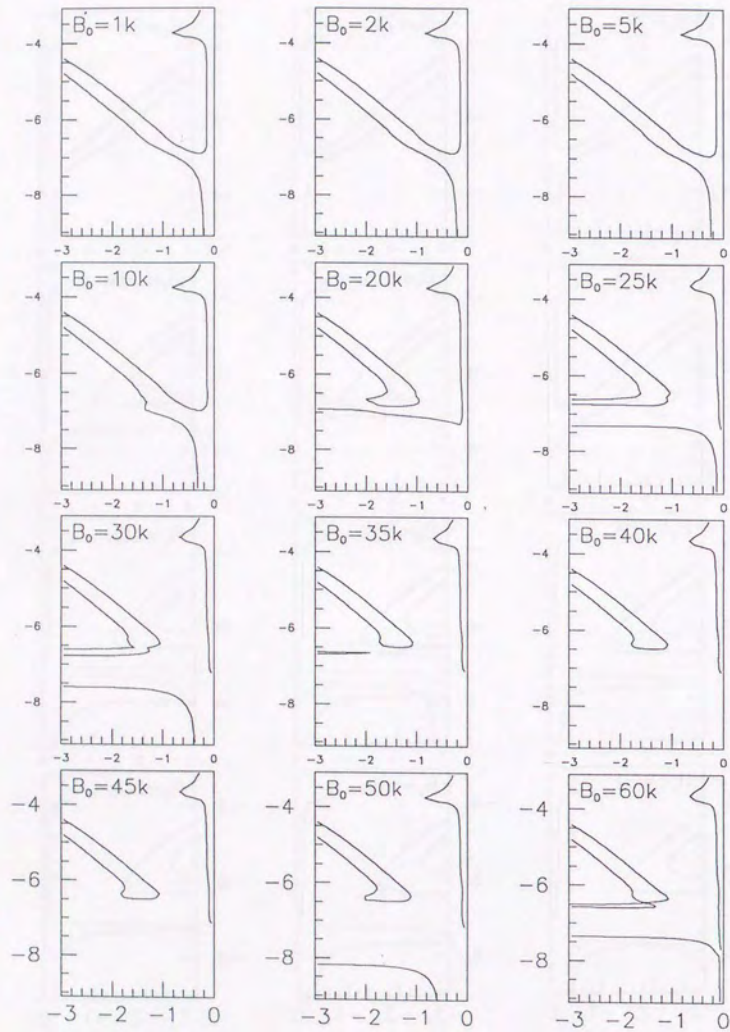
Kamioka

Fig. 7.18 cont.
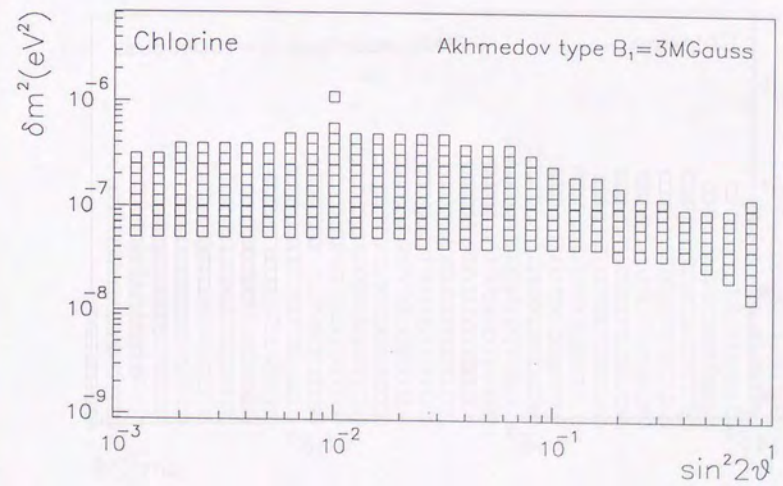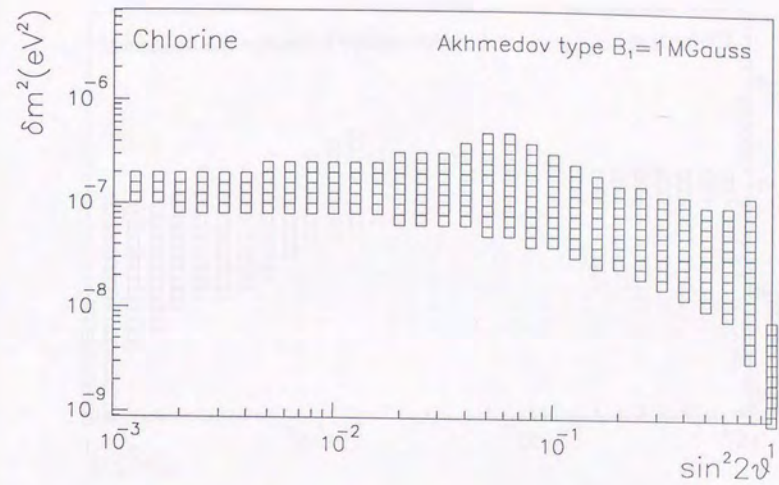
Fig. 7.19

Fig. 7.19 cont.

Fig. 7.19 cont.

Fig. 7.19 cont.

Fig. 7.20

Chlorine & Gallium   Akhmedov type B_t=300kGauss

$\delta m^2 (eV^2)$

$\sin^2 2\vartheta$

Chlorine & Gallium   Akhmedov type B_t=0Gauss

$\delta m^2 (eV^2)$

$\sin^2 2\vartheta$

Chlorine & Gallium   Akhmedov type B_t=100kGauss

$\delta m^2 (eV^2)$

$\sin^2 2\vartheta$

Fig. 7.20 cont.

Chlorine & Gallium   flat field in the convection zone

$\delta m^2 (eV^2)$

$\sin^2 2\vartheta$
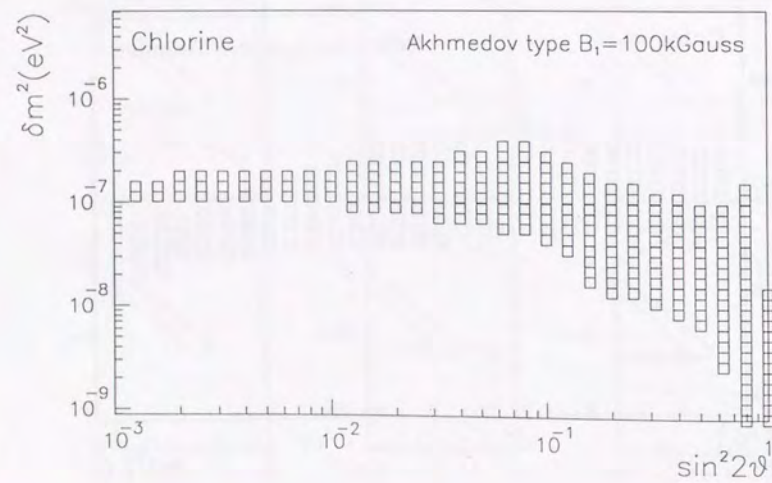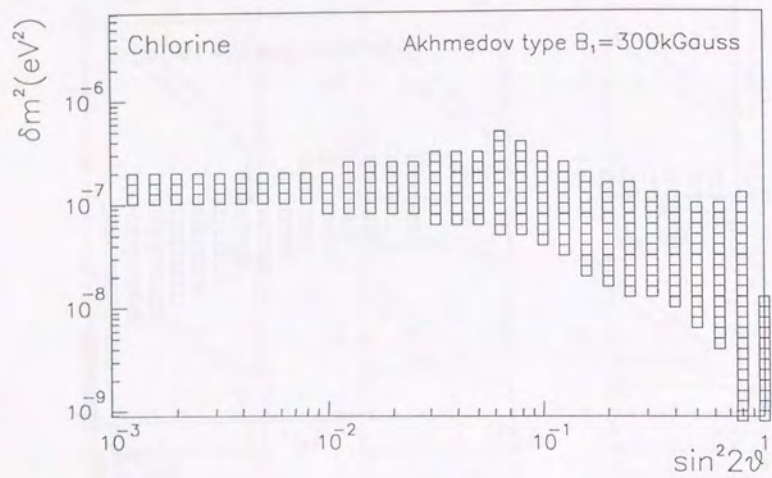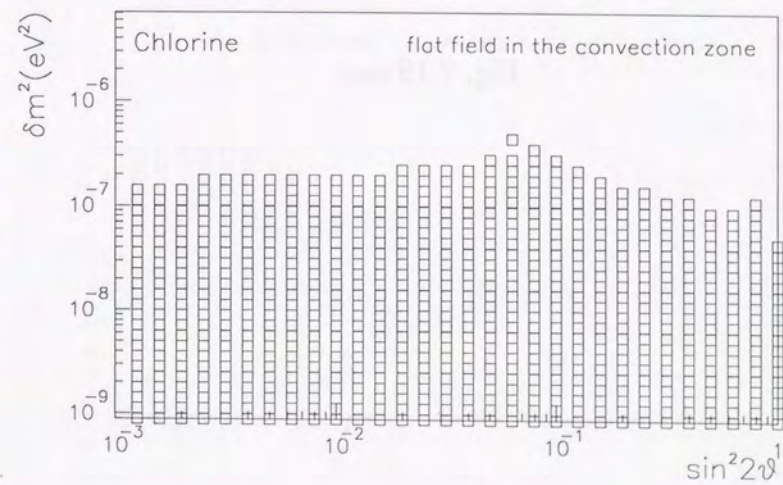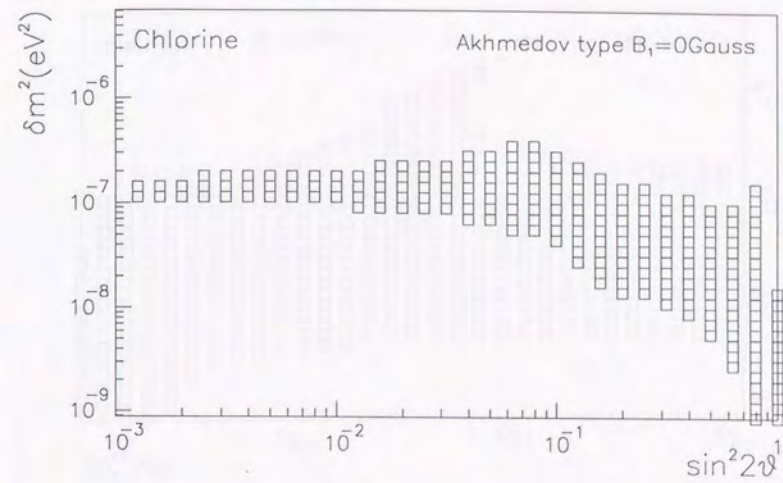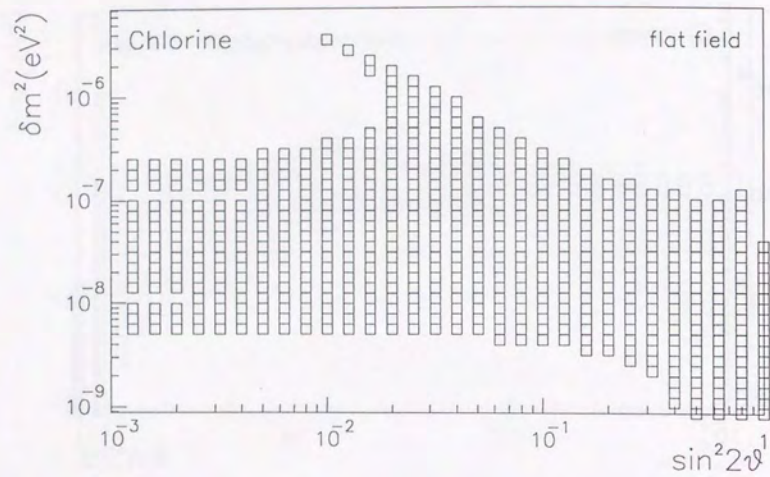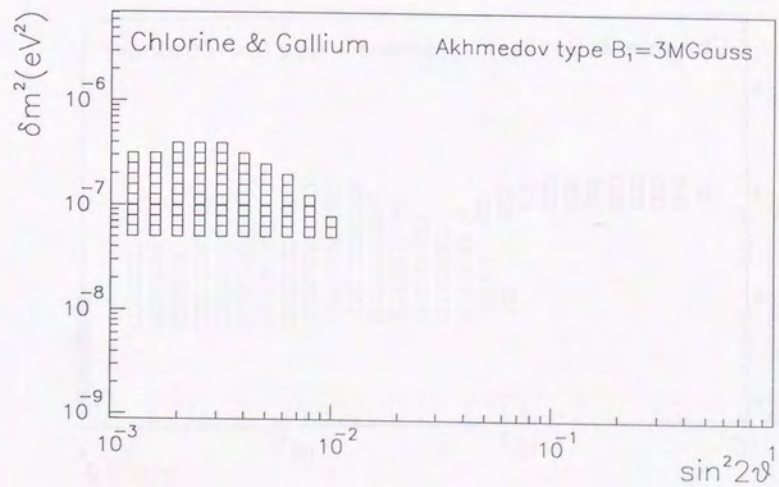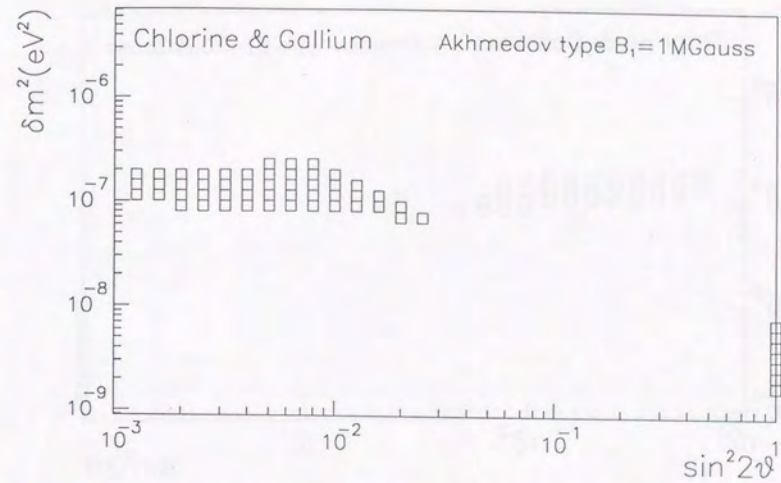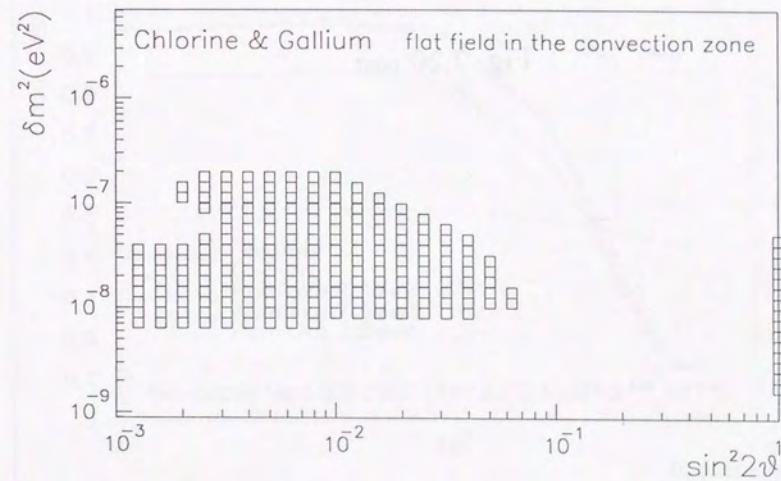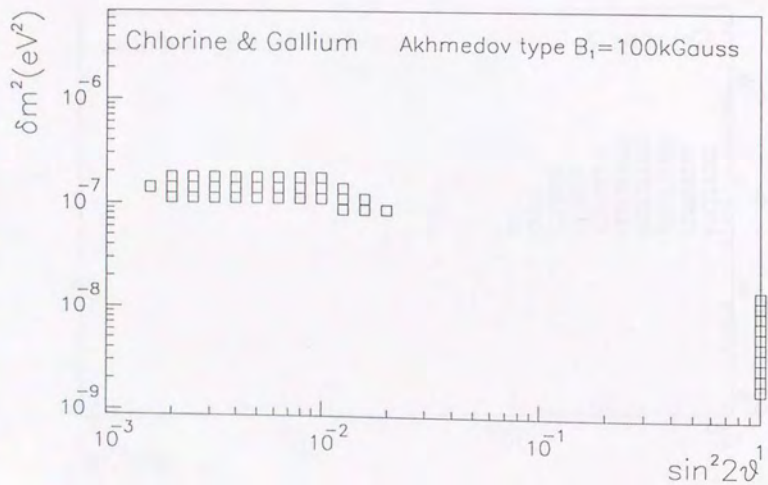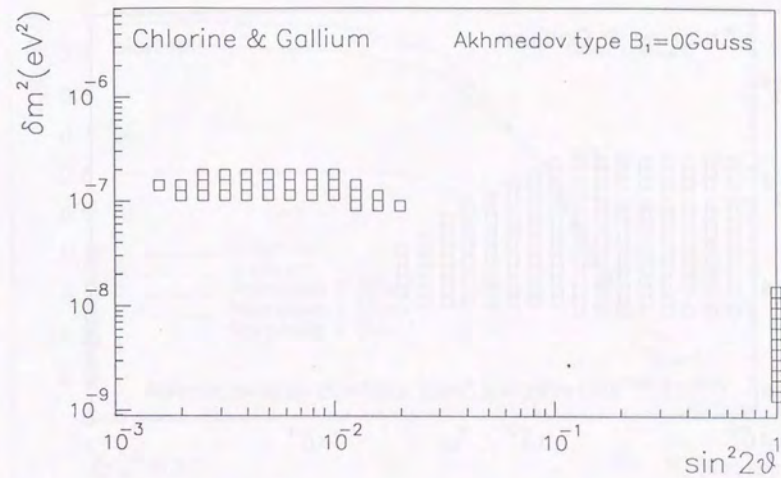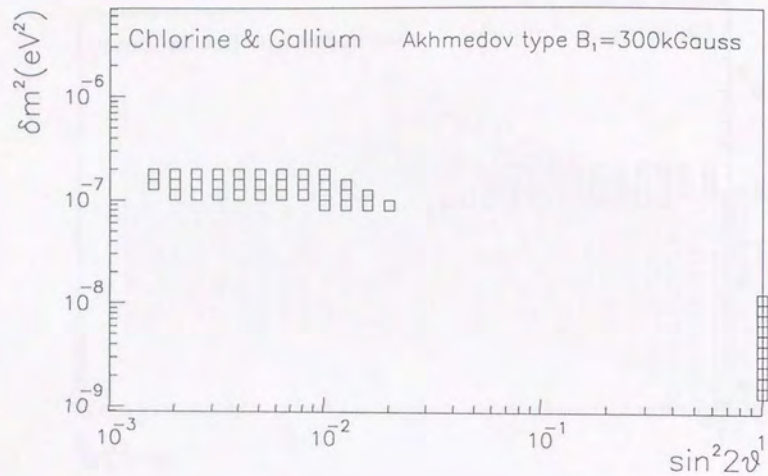
Fig. 7.20 cont.

Fig. 7.20 cont.

Fig. 7.21

Top left plot:

data/SSM

B_{min} B_{max}

Chlorine
Gallium
Kamioka 9.3MeV
Kamioka 7.5MeV
Kamioka 7.0MeV

Akhmedov type $B_1=300$kG $(\delta m^2, \sin^2 2\vartheta)=(10^{-8.45}, 1)$

10^3 10^4 10^5

B_0 (Gauss)

Top right plot:

data/SSM

B_{min} B_{max}

Chlorine
Gallium
Kamioka 9.3MeV
Kamioka 7.5MeV
Kamioka 7.0MeV

flat (convection zone) $(\delta m^2, \sin^2 2\vartheta)=(10^{-8.05}, 1)$

10^3 10^4 10^5

B_0 (Gauss)

Bottom left plot:

data/SSM

B_{min} B_{max}

Chlorine
Gallium
Kamioka 9.3MeV
Kamioka 7.5MeV
Kamioka 7.0MeV

flat (convection zone) $(\delta m^2, \sin^2 2\vartheta)=(10^{-7.55}, 0.01)$

10^3 10^4 10^5

B_0 (Gauss)

Bottom right plot:

data/SSM

B_{min} B_{max}

Chlorine
Gallium
Kamioka 9.3MeV
Kamioka 7.5MeV
Kamioka 7.0MeV

flat $(\delta m^2, \sin^2 2\vartheta)=(10^{-7.45}, 10^{-2.4})$

10^3 10^4 10^5

B_0 (Gauss)

Fig. 7.21 cont.

Fig. 7.21 cont.

Fig. 7.22
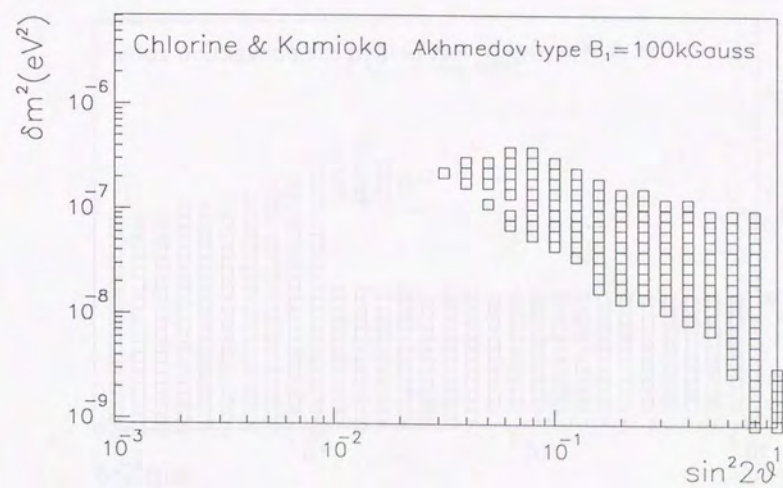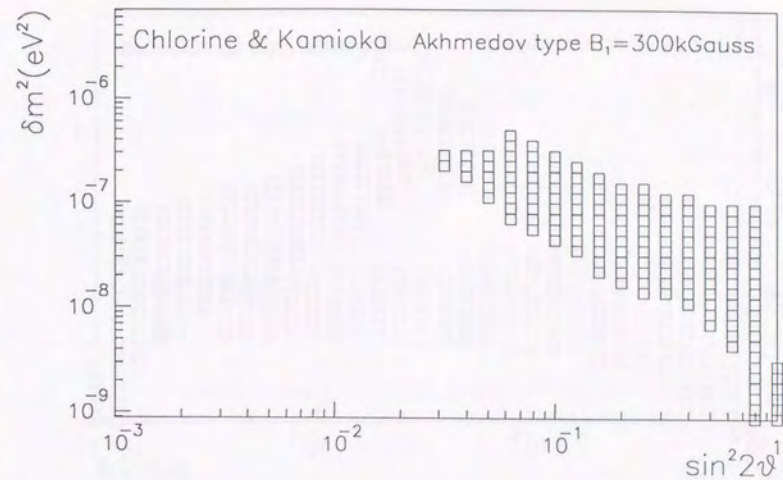
Fig. 7.22 cont.
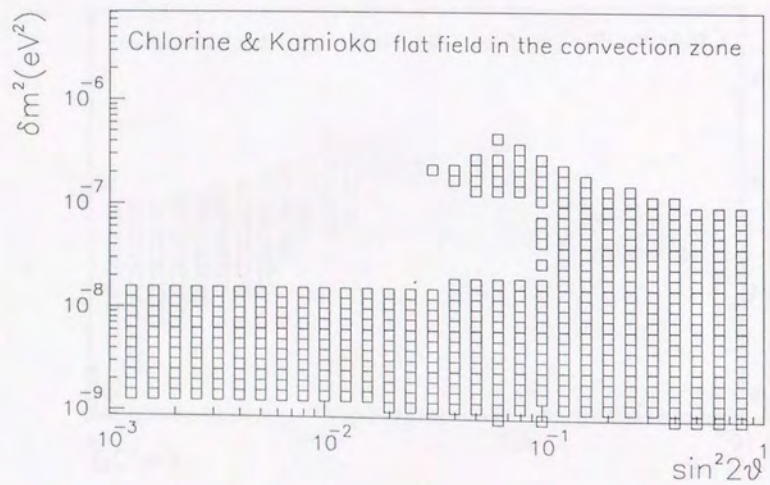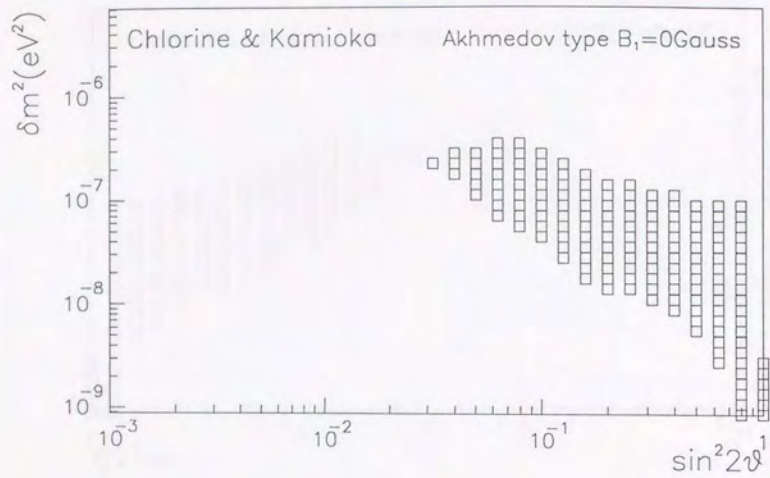
Fig. 7.22 cont.
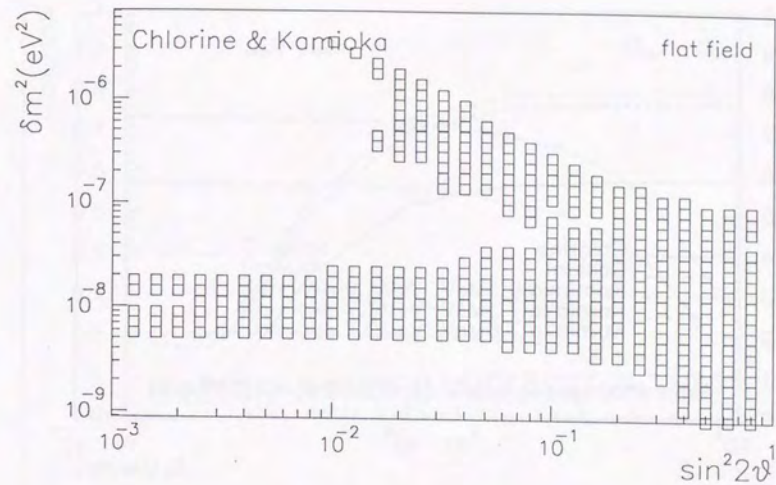
Fig. 7.22 cont.

Fig. 7.22 cont.
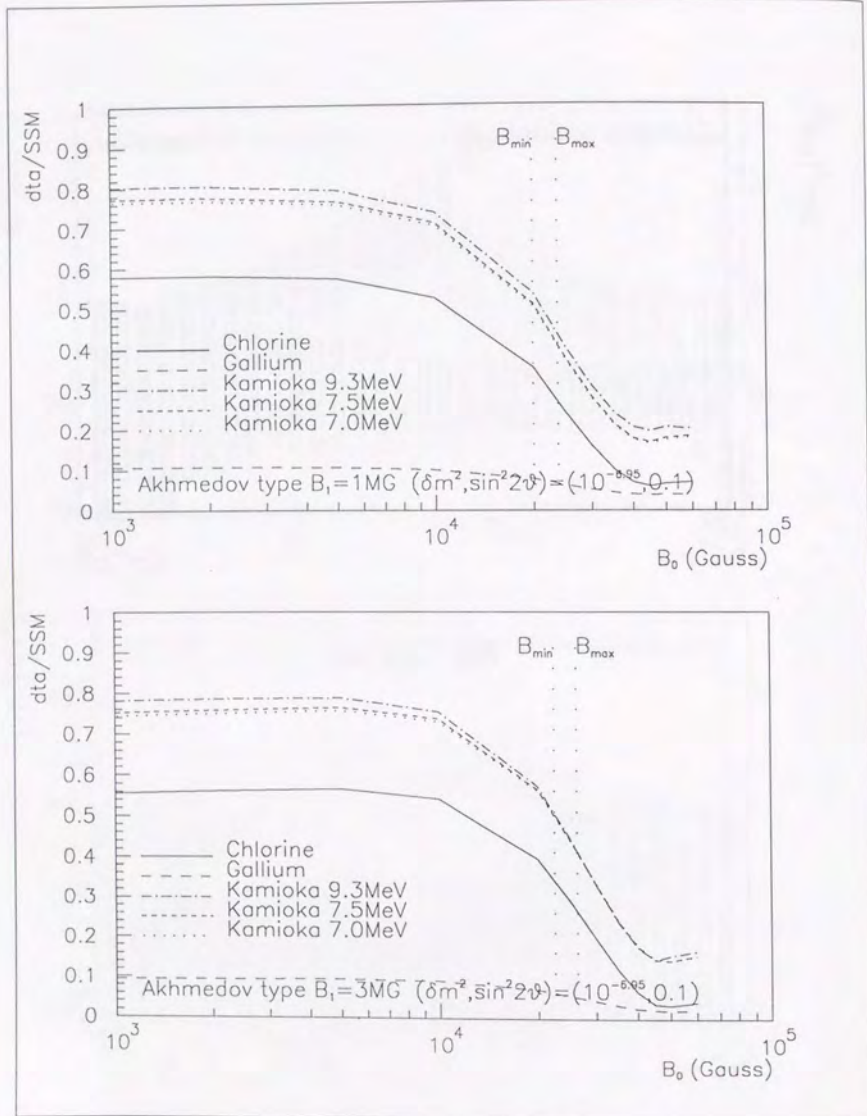
Fig. 7.23
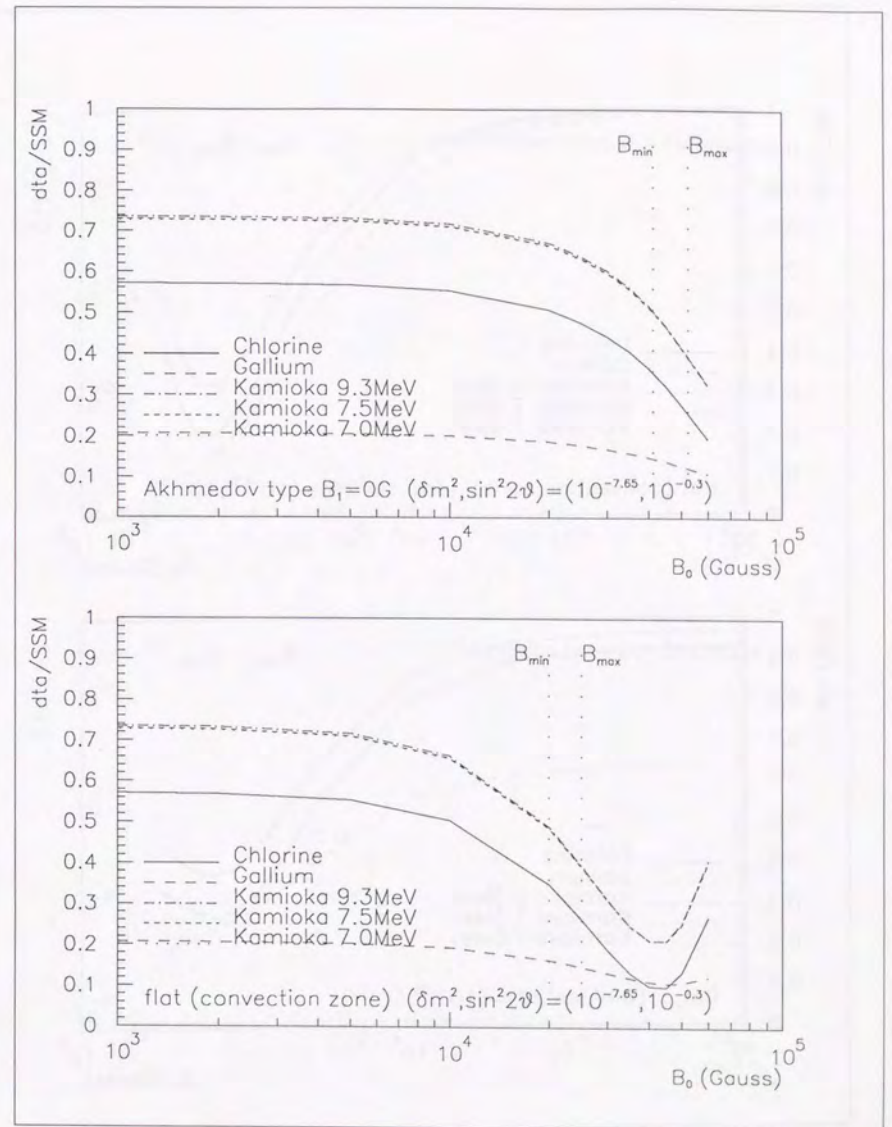
Fig. 7.23 cont.

Fig. 7.23 cont.

Fig. 7.24

$\delta m^2(eV^2)$ — All — Akhmedov type $B_1=300kGauss$ — $\sin^2 2\vartheta$

$\delta m^2(eV^2)$ — All — Akhmedov type $B_1=100kGauss$ — $\sin^2 2\vartheta$

Fig. 7.24 cont.

$\delta m^2(eV^2)$ — All — Akhmedov type $B_1=0Gauss$ — $\sin^2 2\vartheta$

$\delta m^2(eV^2)$ — All — flat field in the convection zone — $\sin^2 2\vartheta$
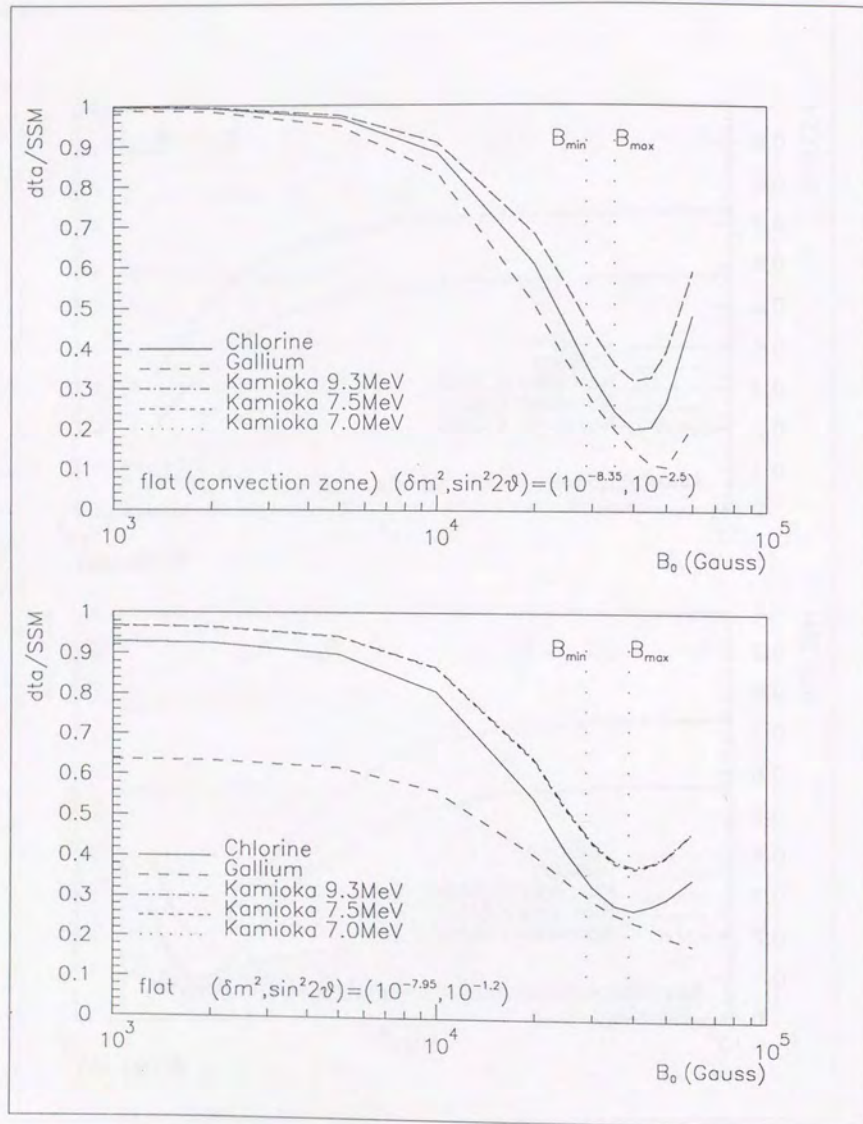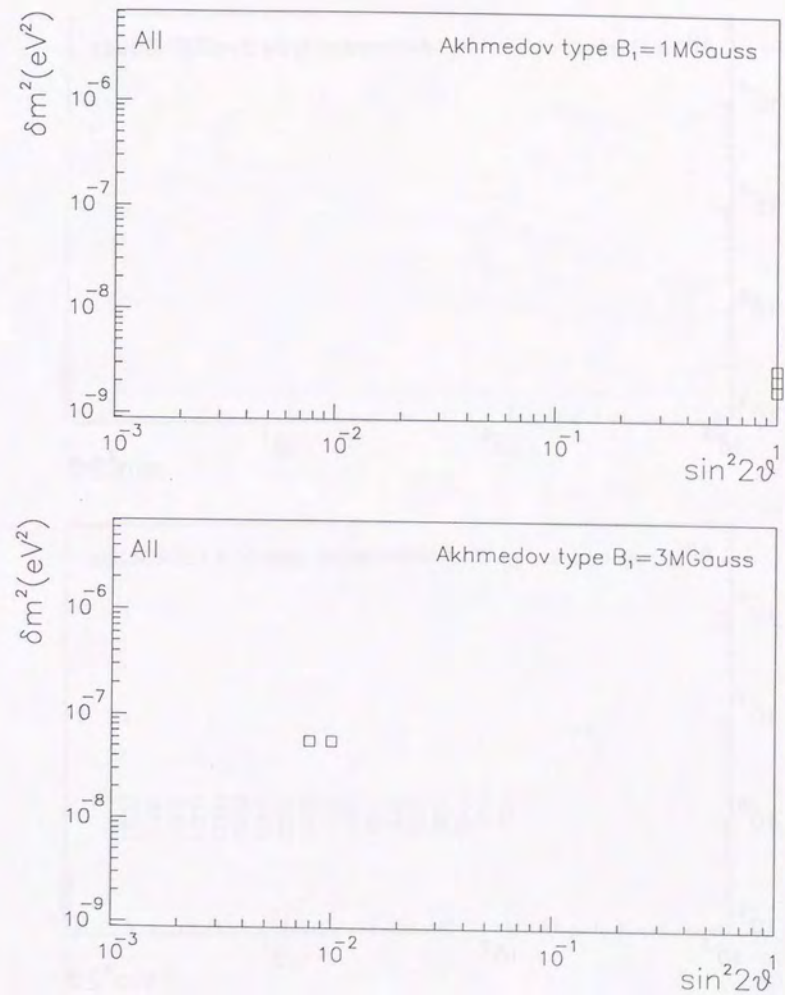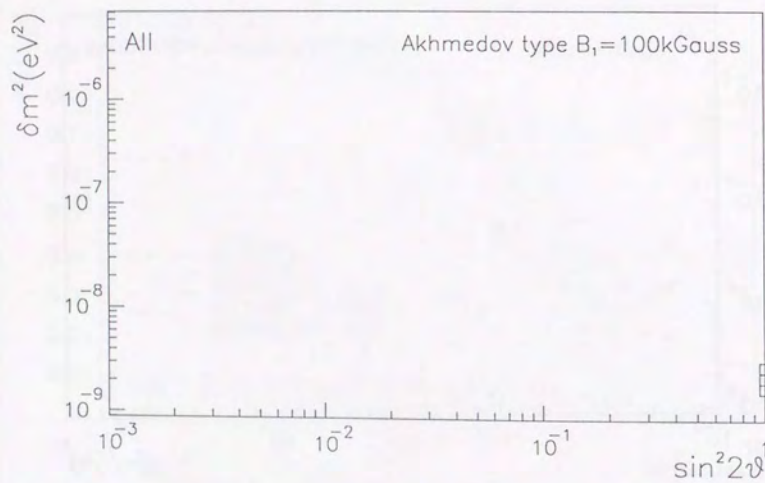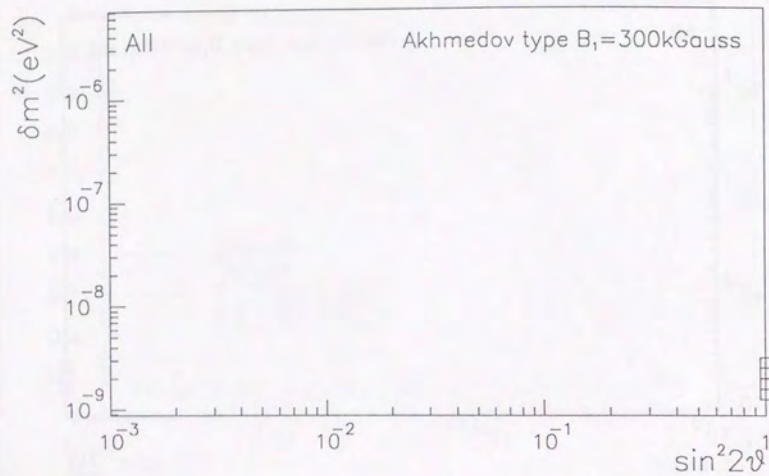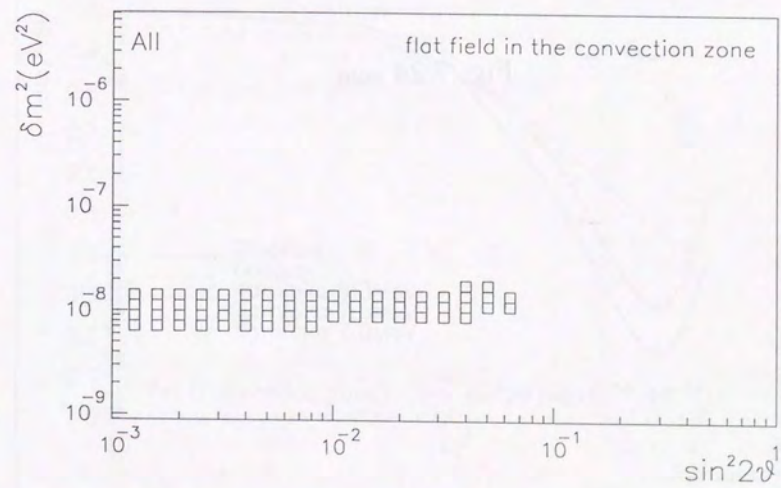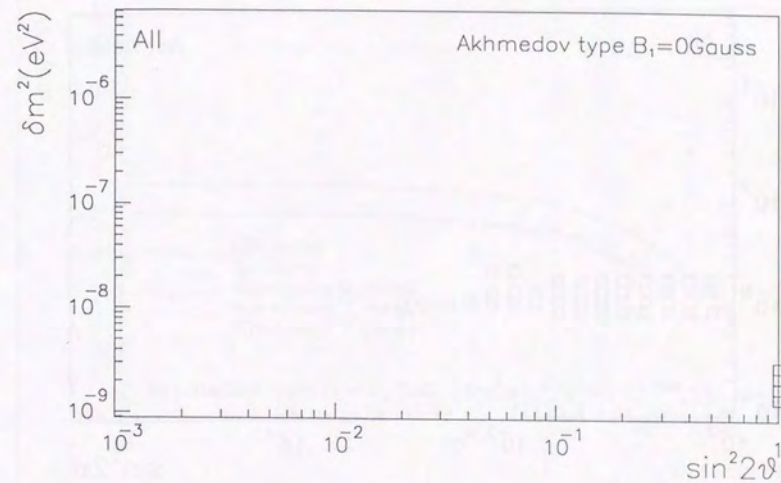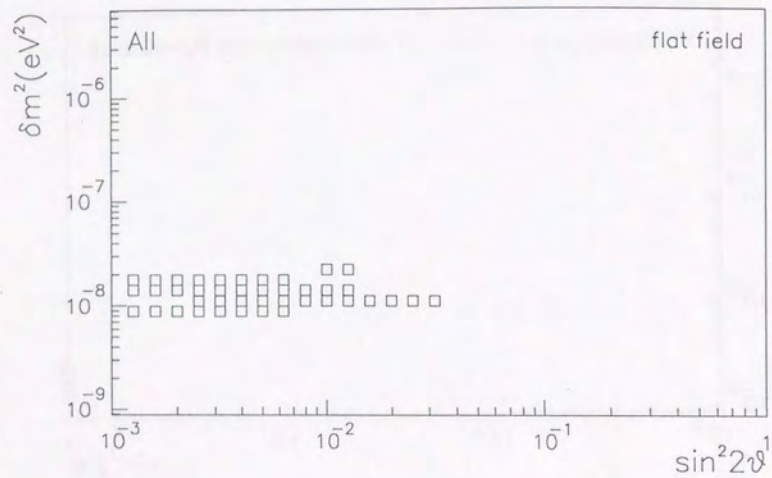
Fig. 7.24 cont.

Fig. 7.24 cont.
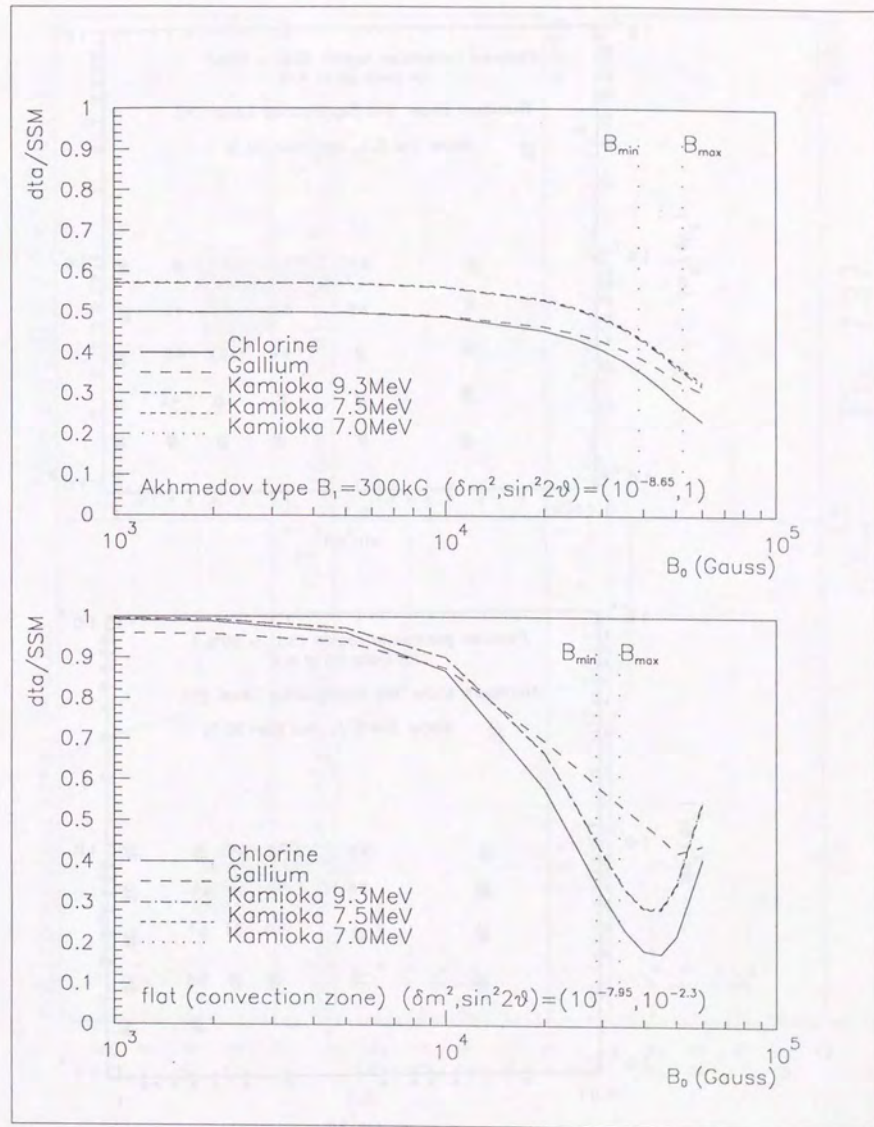
Fig. 7.25
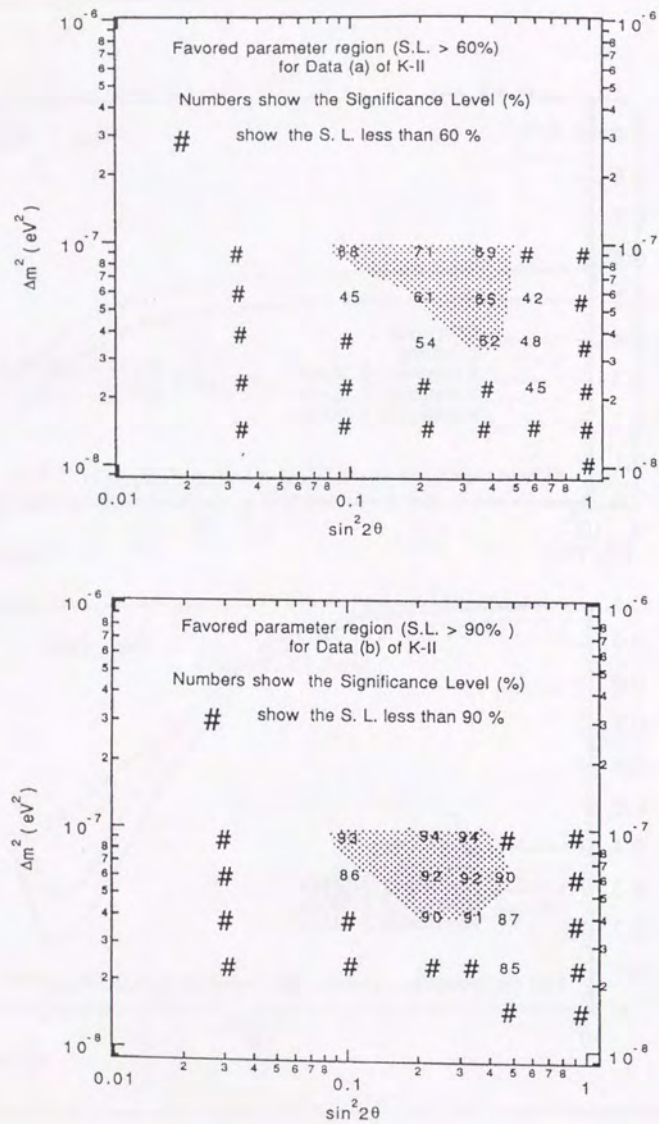
Fig. 7.26
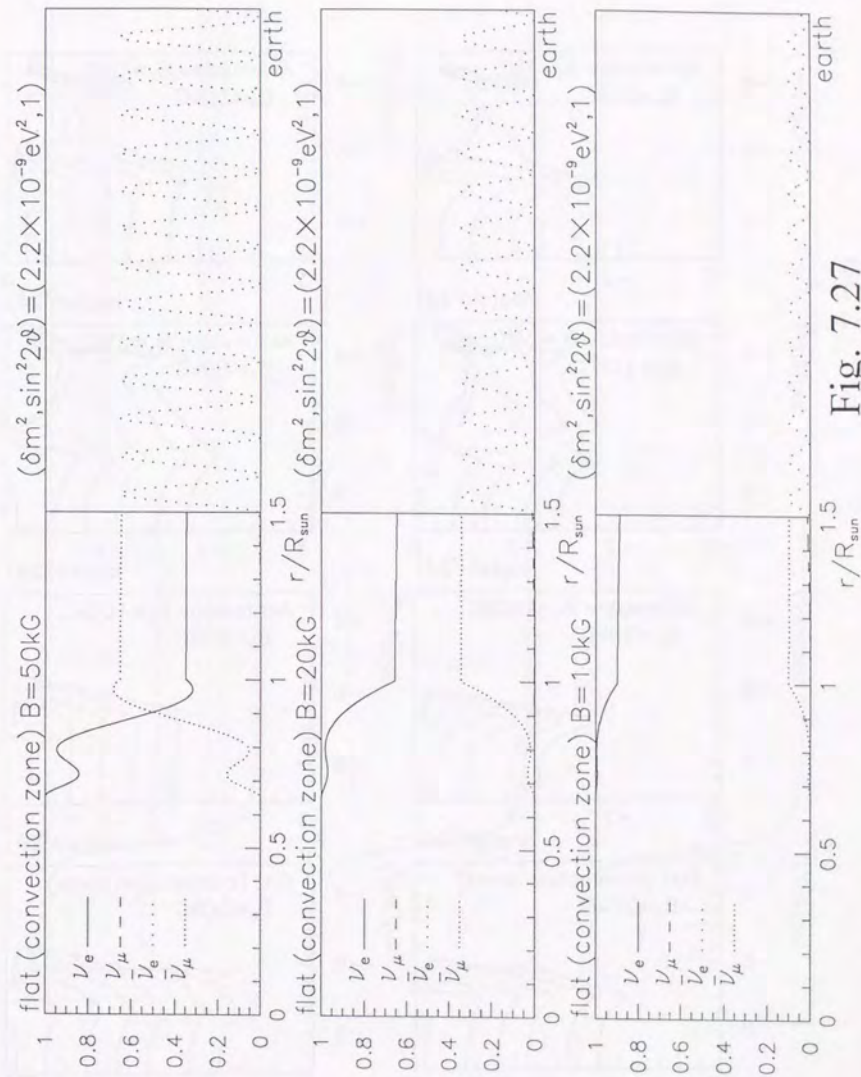
Fig. 7.27
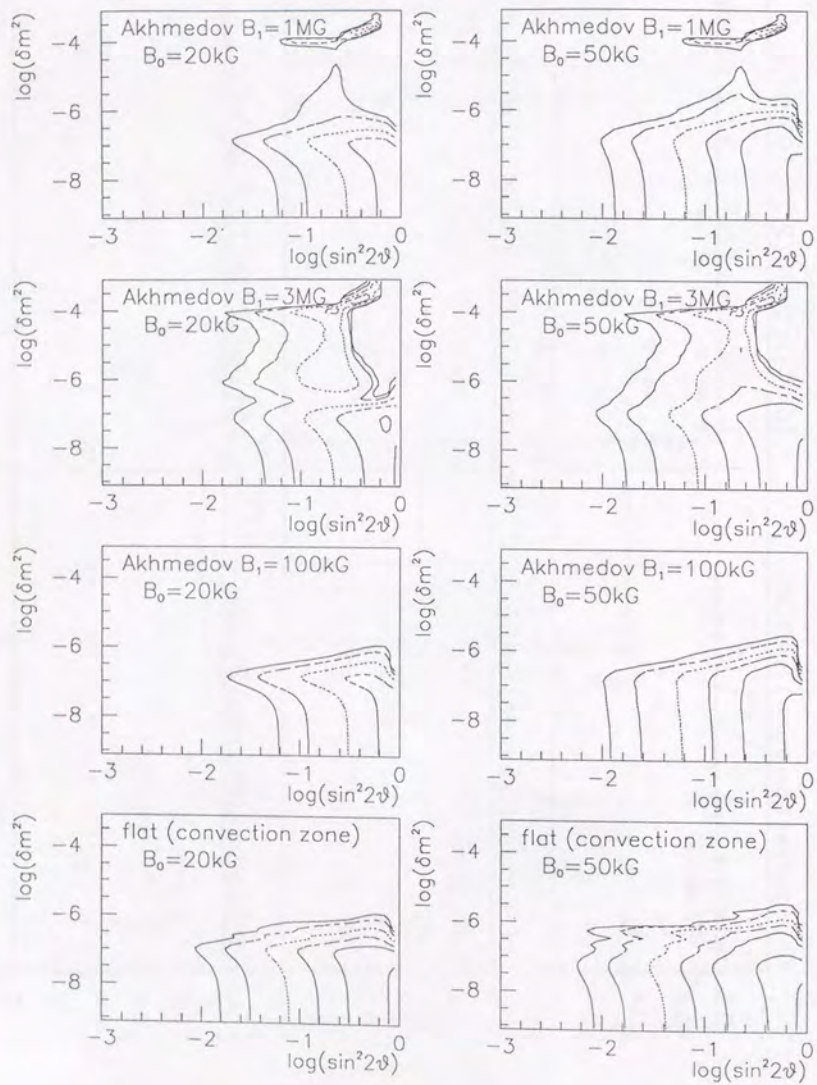
Fig. 7.28
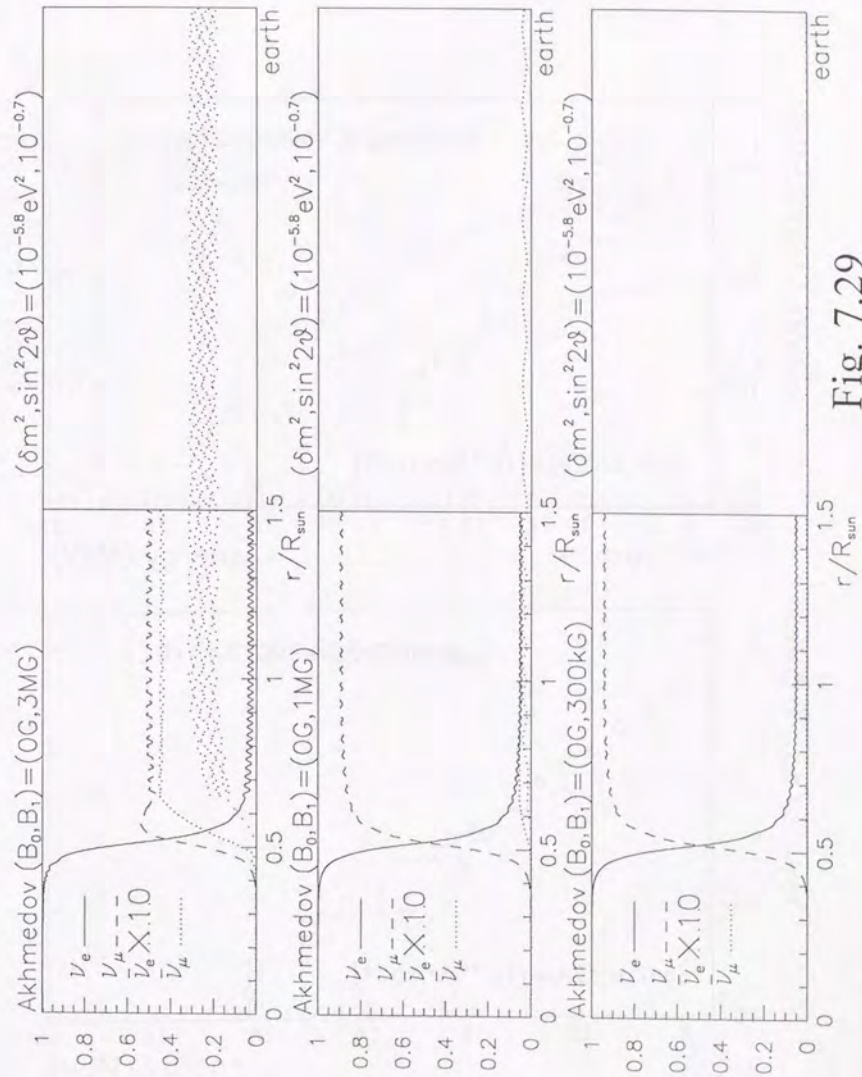
Fig. 7.29
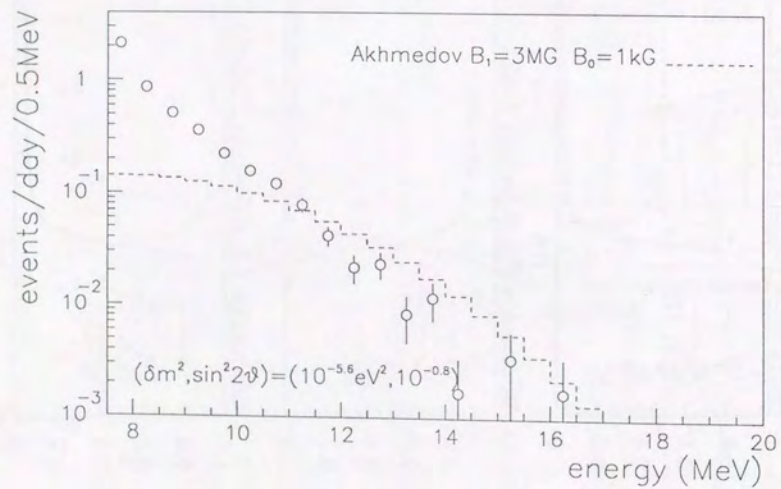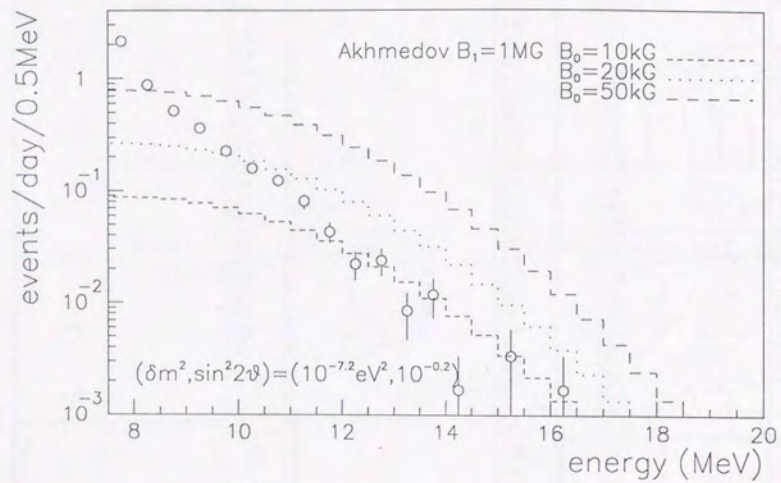
Fig. 7.30
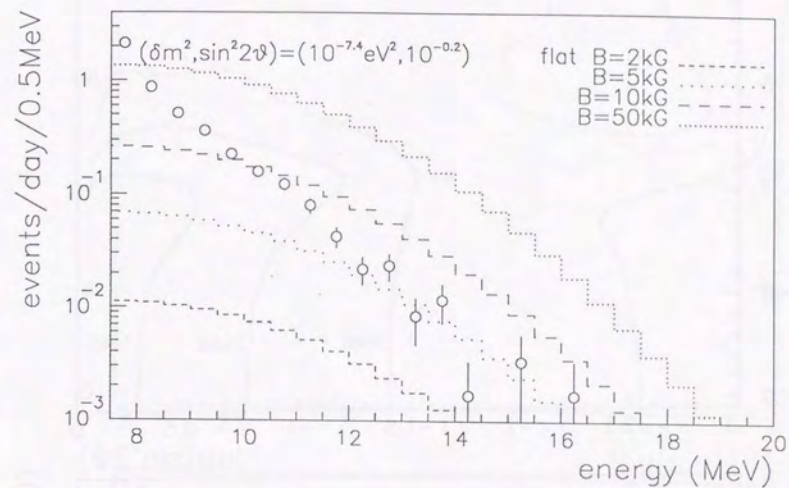
Fig. 7.30 cont.

Fig. 7.31

Fig. 7.31 cont.

Fig. 7.31 cont.
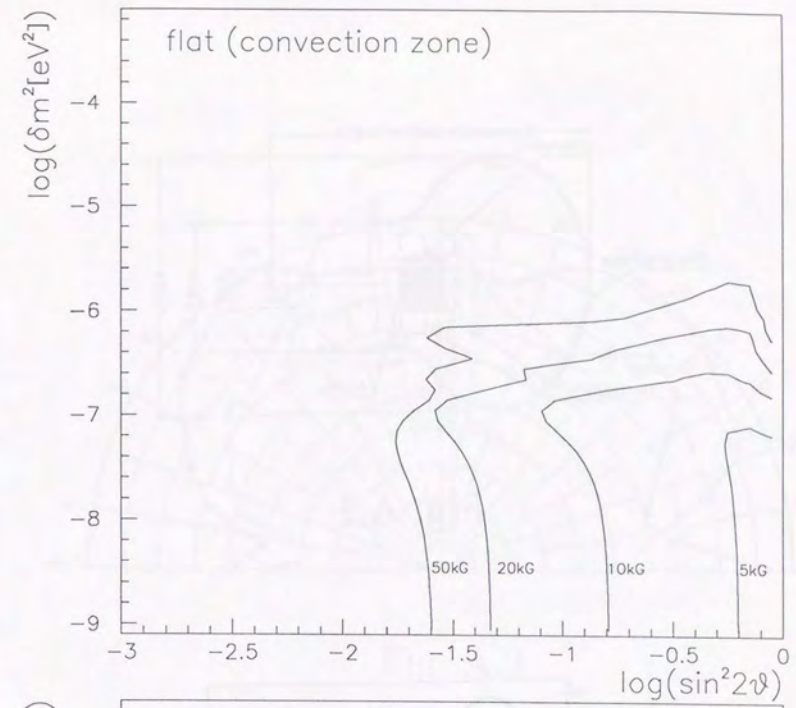
Fig. 7.31 cont.
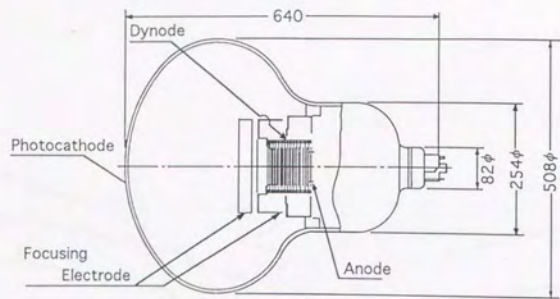
Fig. A.1

Fig. A.2

Fig. A.3

Fig. A.4

Fig. A.5

Cone-Shape Mumetal Shield (0.35mm thick)

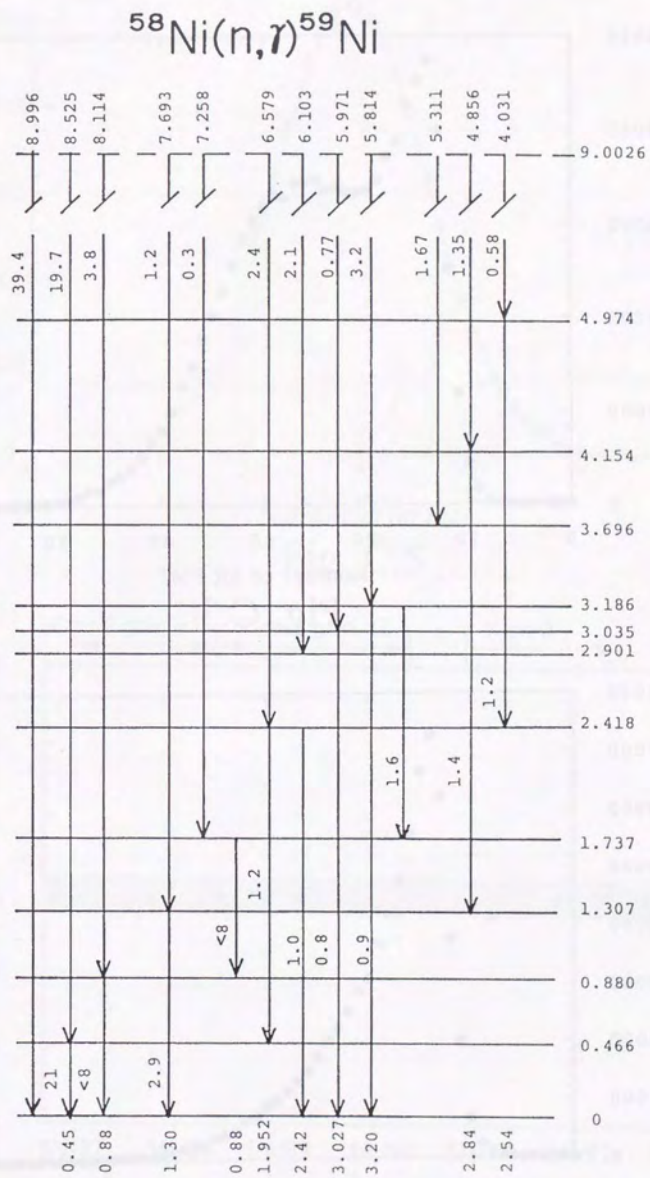Mesh Mumetal Shield (1.5mm φ)
89% light transparency
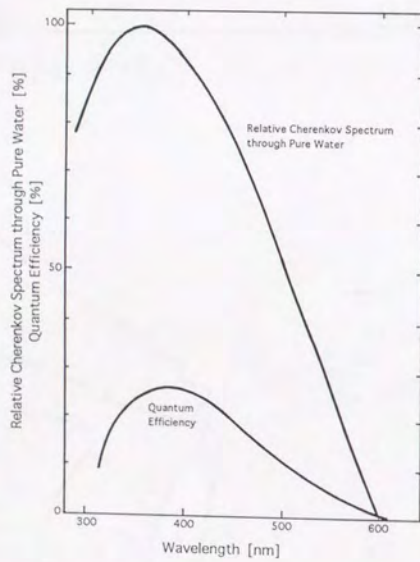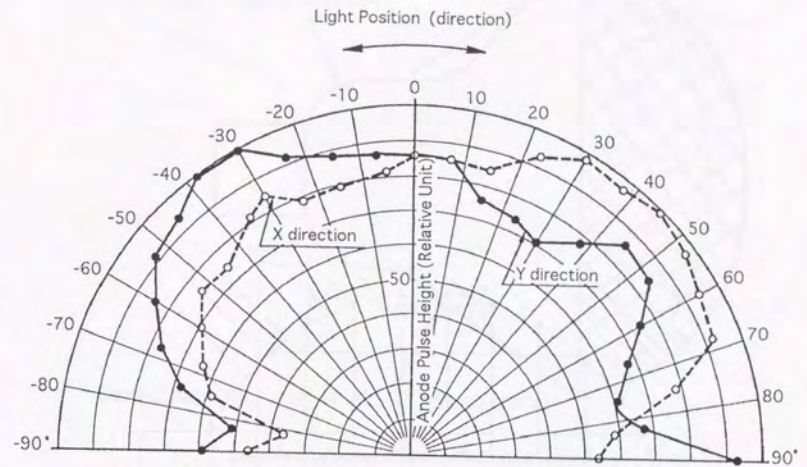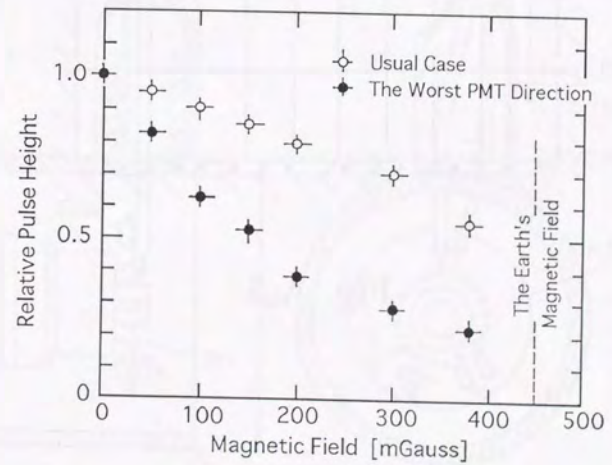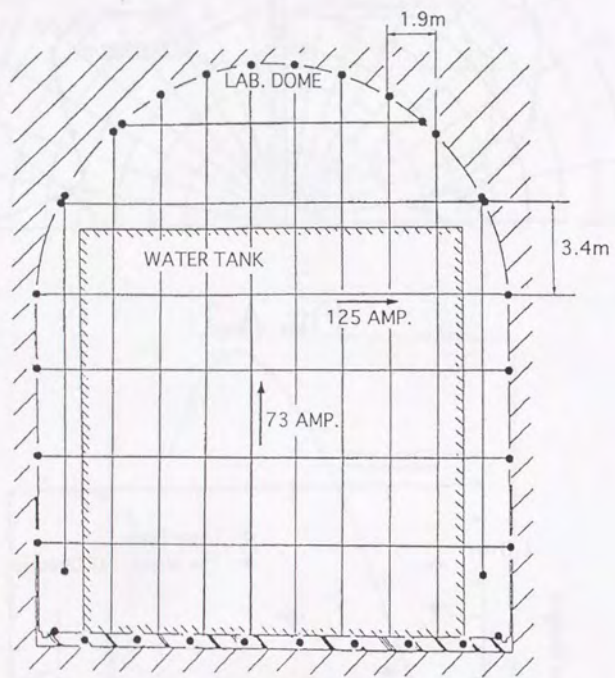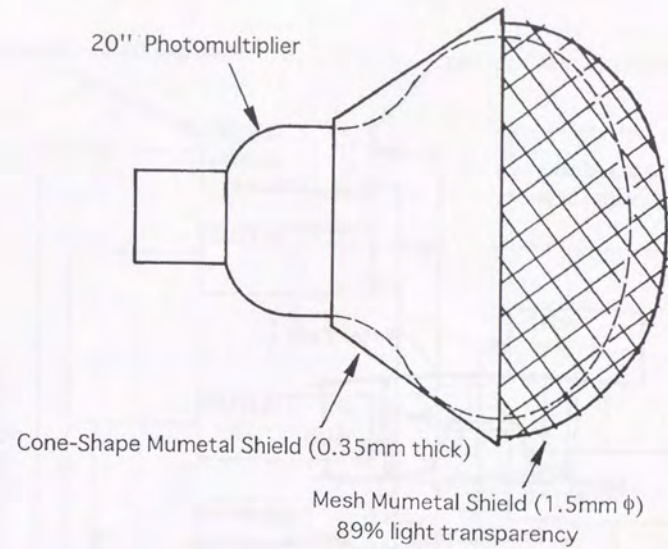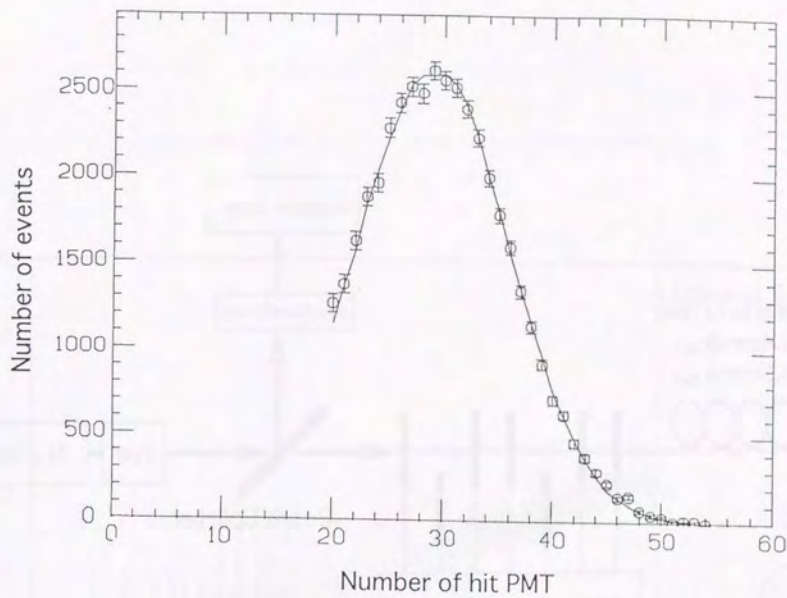
Fig. A.6
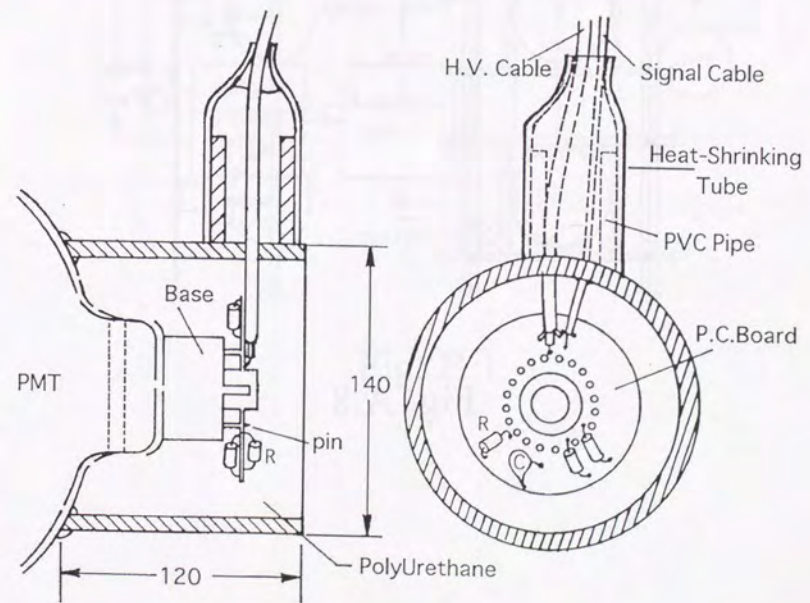
Fig. A.7

Fig. A.8

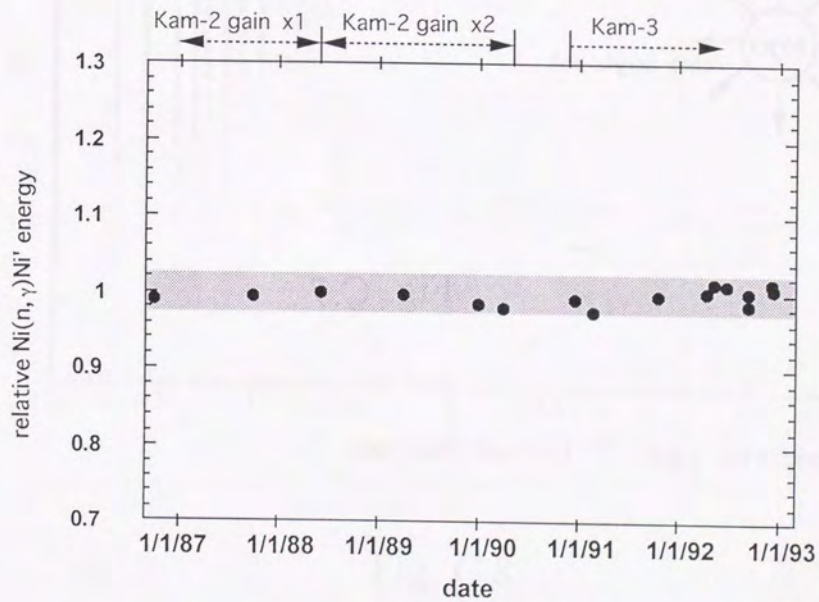Fig. B.1

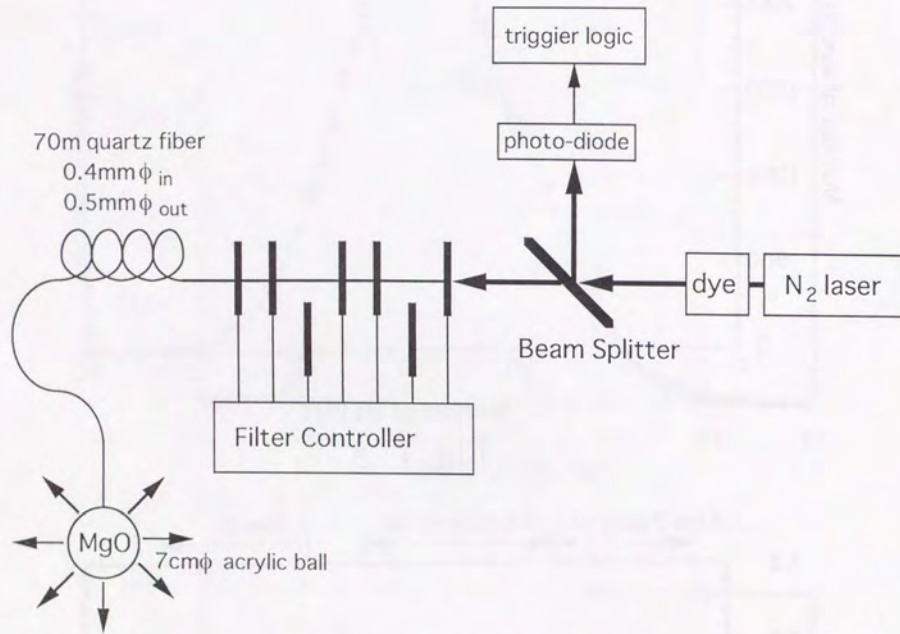Fig. C.1

^{58}Ni(n,γ)^{59}Ni
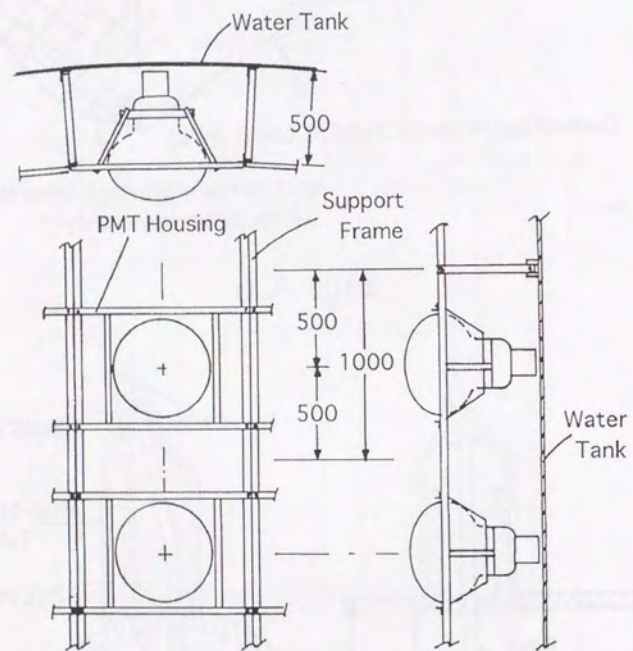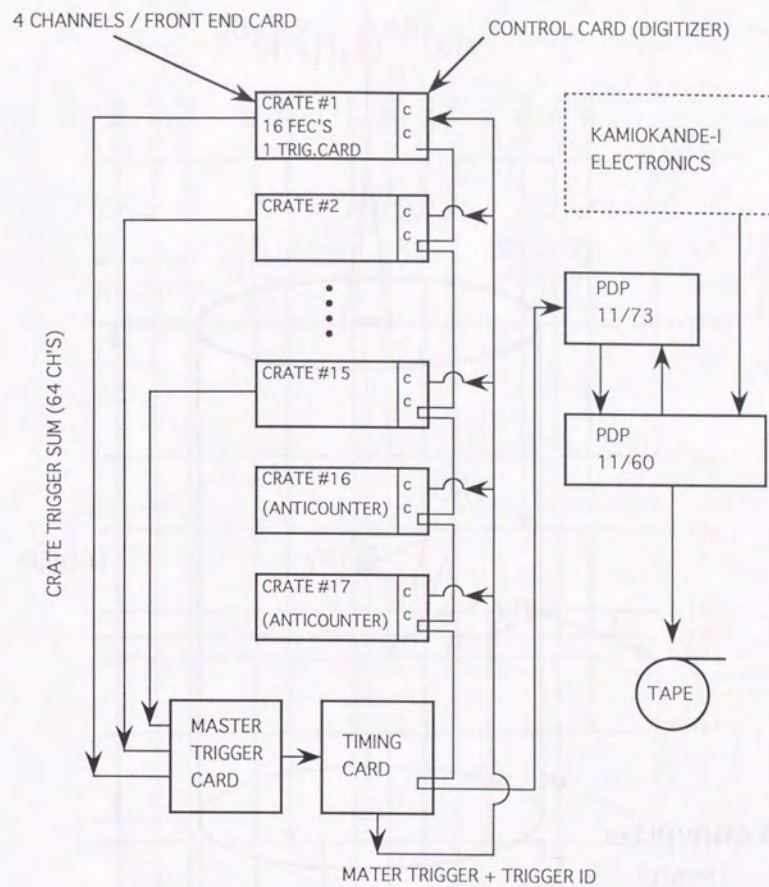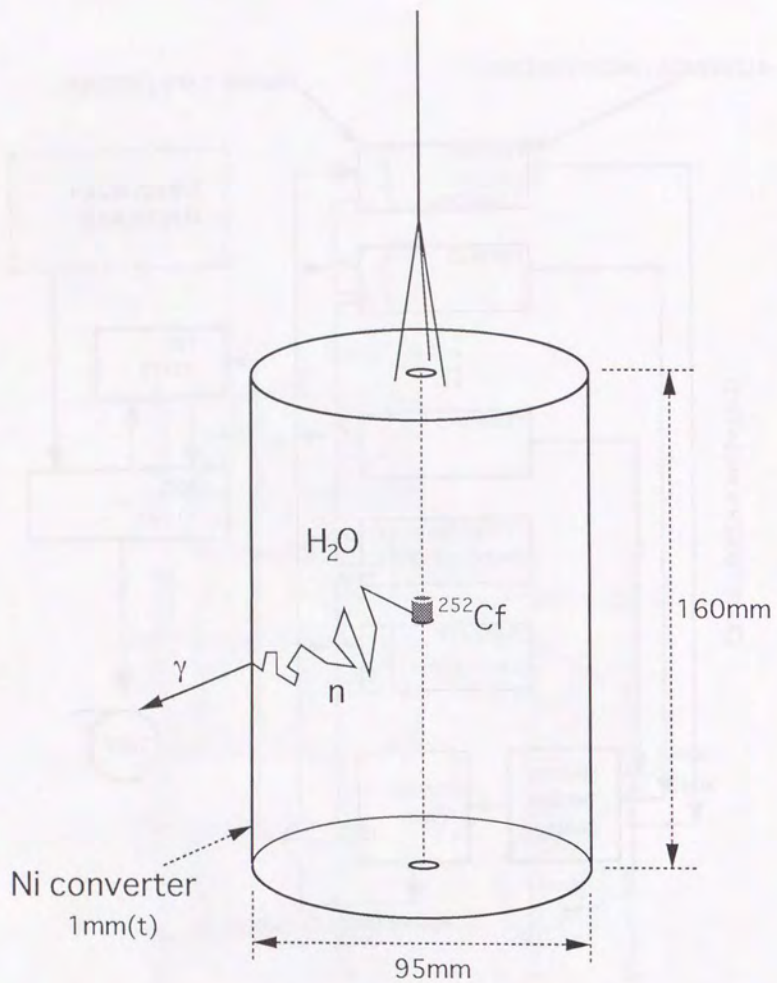
Fig. C.2

Fig. C.3

Fig. C.4

Fig. C.5

Fig. C.6

70m quartz fiber
0.4mm φ in
0.5mm φ out

triggier logic

photo-diode

Beam Splitter

dye

N₂ laser

Filter Controller

MgO

7cm φ acrylic ball

Fig. C.7

channel 5-A

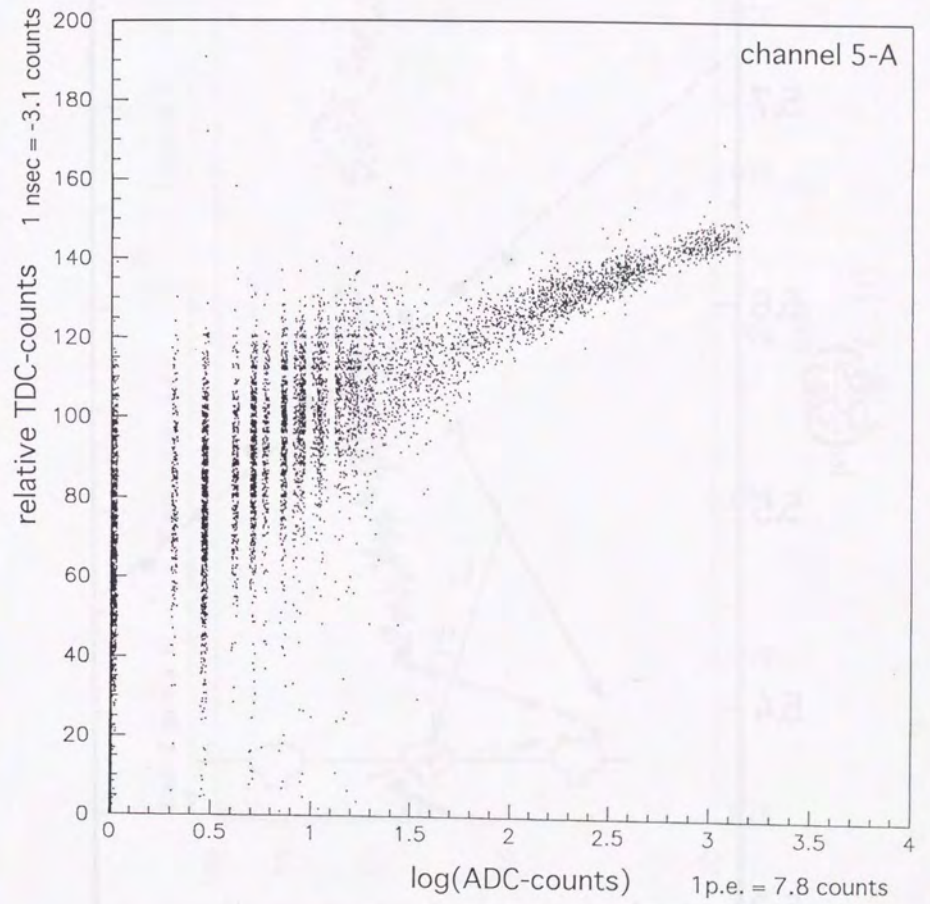relative TDC-counts   1 nsec = -3.1 counts
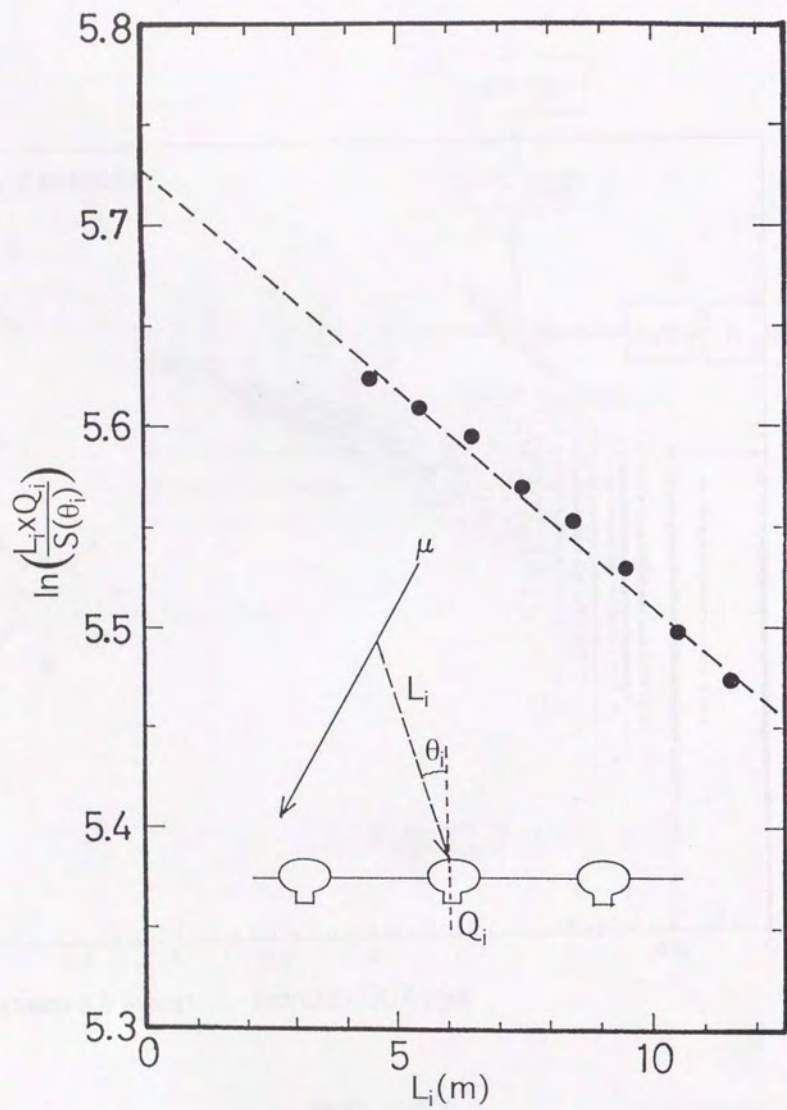
log(ADC-counts)   1p.e. = 7.8 counts
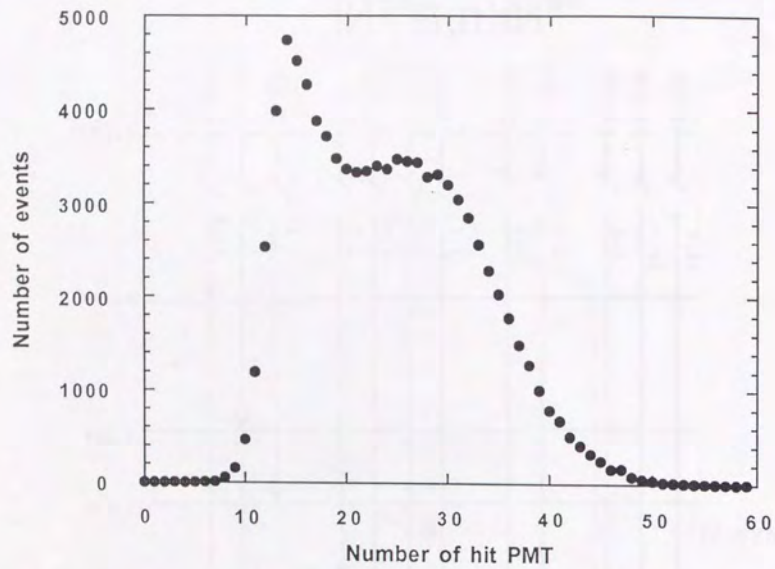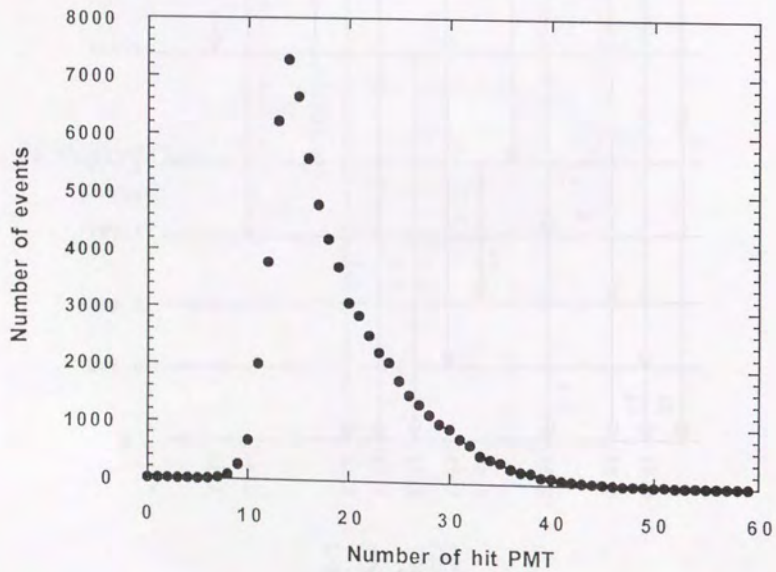
Fig. C.8

Fig. C.9
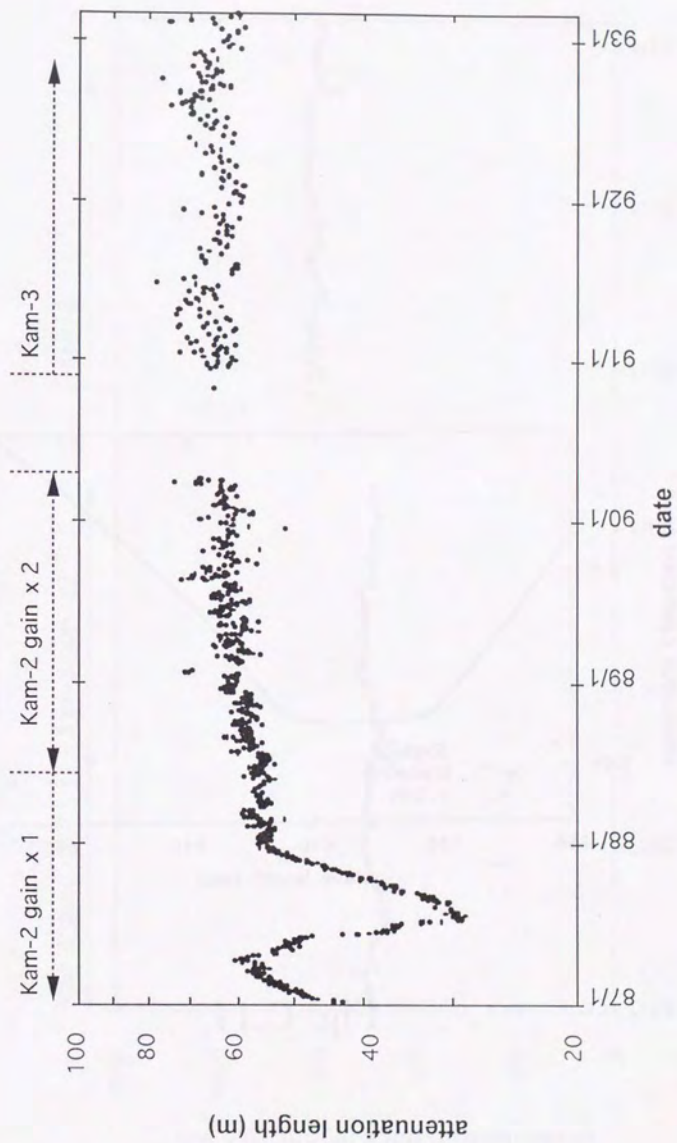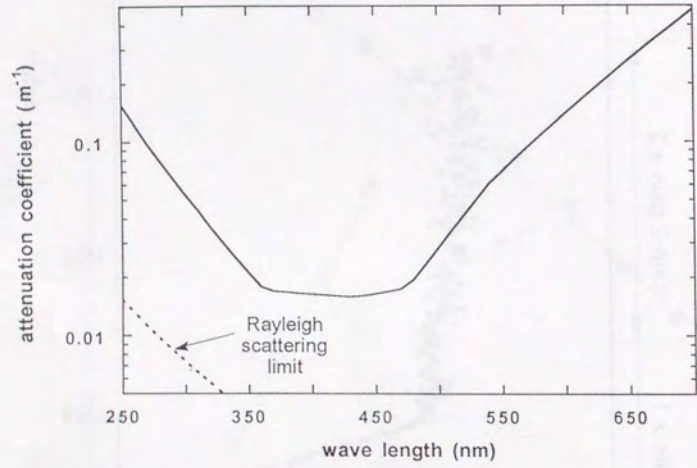
Fig. C.10

Fig. C.11

Fig. C.12
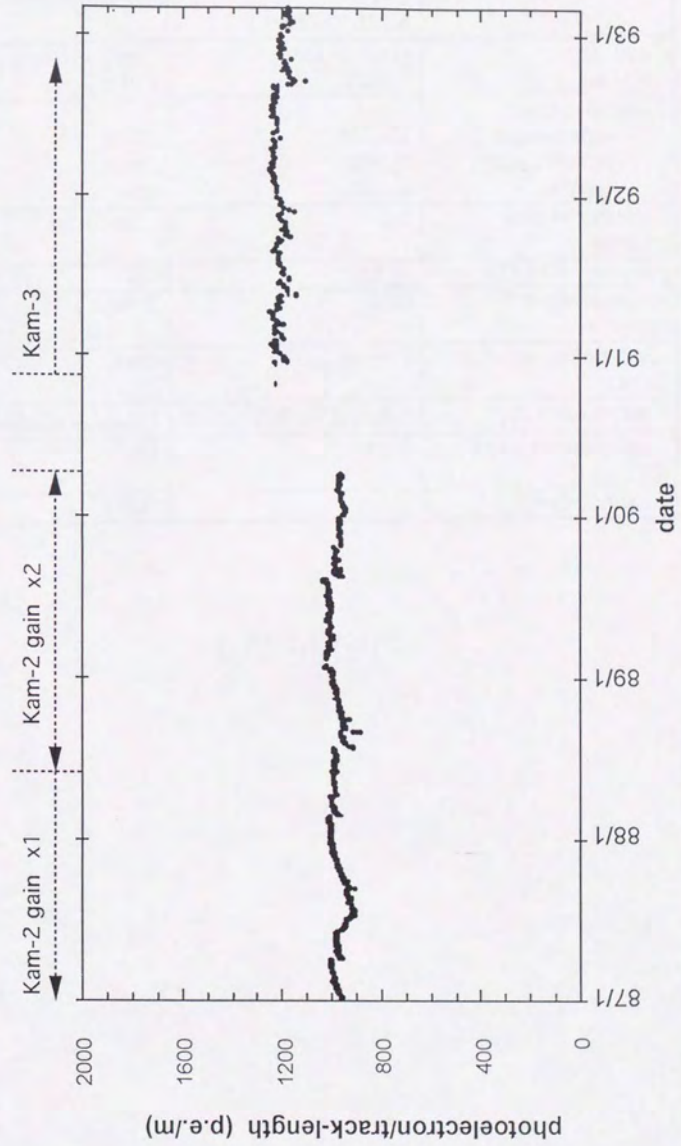
Paramters	Super-Kamiokande	Kamiokande-3
Total size Total mass	$41mh \times 39m\phi$ 50000t	$16mh \times 19m\phi$ 4500t

Fiducial mass
    supernova ν
    proton decay
    solar ν
	
	32000t
	22000t
	22000t
		
		2140t
		1040t
		680t

Tickness of anti-counter	2m	1.2m~1.5m
Number of PMTs	11200	947
Photosensitive coverage	40%	$20\% \times 1.27$ (light reflector)
PMT timing resoluton @1p.e.	2.5nsec	4nsec
Energy resolution	$16\%/\sqrt{E/10MeV}$	$19\%/\sqrt{E/10MeV}$
Position resolution @10MeV	50cm	1m
Analysis threshold	5MeV	7MeV

Table D.1