ON THE KAMIOKANDE ^{8}B SOLAR NEUTRINO MEASUREMENT

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Abstract

We study the reconstruction resolution $E[\langle\theta^2\rangle]^{1/2}$ of the arrival direction in the ^{8}B neutrinos measurement by water Cherenkov detector and found the discrepancy with about 70% between the theoretical and experimental values for the root mean square scattering angles of low energy electrons. This discrepancy implies the suspected measurement for the scattering distribution of low energy electrons by the water Cherenkov detector.

Key words:

1 Reconstruction resolution $E[\langle\theta^2\rangle]^{1/2}$ of the arrival direction

The expected angular distribution of electrons recoiled in the water detector should be represented by the angular deflection in ν_e-e^- scattering folded by the reconstruction ambiguity with the resolution angle of $E[\langle\theta^2\rangle]^{1/2}$ for the incident direction of electrons in the Kamiokande water detector:

$$f(\cos\theta_{sun})d\cos\theta_{sun} =$$

$$\frac{d\cos\theta_{sun}}{\pi}\int_0^{\infty} dE_\nu\,\phi(E_\nu)\int_{-1}^{1} d\cos\theta'\frac{d\sigma}{dy}\frac{dy}{d\cos\theta'} \times\frac{1}{E[\langle\theta^2\rangle]}\int_0^{2\pi}\exp[-\frac{(\vec{\theta}_{sun}-\vec{\theta}')^2}{E[\langle\theta^2\rangle]}]d\varphi', \quad (1)$$

where θ_{sun} denotes an angle between a direction of electron and the radial direction of the sun. The differential energy spectrum $\phi(E_\nu)dE_\nu$ represents the solar neutrino flux and y denotes a fraction of kinetic energy transferred from neutrino. The mean square error of reconstructed direction of the recoil electron, $E[\langle\theta^2\rangle]$, should be evaluated from the mean square deflection angle of electrons weighted by emitted numbers of Cherenkov photons. We have

$$E[\langle\theta^2\rangle] = \int\langle\theta^2\rangle\frac{dN}{dt}dt/\int\frac{dN}{dt}dt, \quad (2)$$

where $\langle\theta^2\rangle$ indicates mean square deflection angle of electrons after receiving multiple scattering process in passage of a thickness t. The $\langle\theta^2\rangle$ can be evaluated from the angular distribution of electrons predicted through the multiple scattering theory, e.g., Williams theory (1939), Molière theory (1947) and others (Scott, 1963). But it must be noticed that the specific approximations are applied in the respective theories. In the EGS4 code (Nelson et al., 1985) used at the Kamiokande analyses (Hirata et al., 1991b), Molière theory is adopted. Although it is recognized most advanced in getting angular distribution, it gives divergence in $\langle\theta^2\rangle$, as well known (Scott, 1963), since

Table 1: Comparison of Data/SSM$_{BP92}$ using various scattering theories.

scattering theory	*data/SSM$_{BP92}$*	
Kamiokande-EGS4	maxium likelihood method:	0.50±0.10
Mott with reduction function	maxium likelihood method:	0.45±0.10
Mott without reduction function	maxium likelihood method:	0.51 (see text)
	χ^2 method:	0.43 (see text)
Williams with reduction function	maxium likelihood method:	0.48±0.10
EGS-like with reduction function	maxium likelihood method:	0.42±0.10

it starts from an approximated single scattering formula of a form $\theta^{-4}2\pi\theta d\theta$ with no upper bound in its angular range. More precise result can be obtained not through the multiple scattering theory but directly through integration of the single scattering formula,

$$\langle\theta^2\rangle = \int_0^t \mu_2(E)dt = \int_0^t dt \iint \theta^2\sigma(\theta)d\omega, \qquad (3)$$

where $\mu_2(E)$ means the mean square angle of the single scattering formula.

2 Comparison of various $E[\langle\theta^2\rangle]^{1/2}$

For studying the Kamiokande $E[\langle\theta^2\rangle]^{1/2}$ obtained by Monte Calro method using EGS4 code, we evaluate analytically the value using the multiple scattering theory giving Williams' distribution under the gaussian approximation (Rossi and Greisen, 1941) and also the other values derived from Molière theory in numerical calculation and corrected $E[\langle\theta^2\rangle]^{1/2}$ by the more precise single scattering formula of Mott (1928) by numerically. The Molière one under Gaussian approximation and Mott one are shown by a broken-g and by a solid curve-m in Fig. 1. For reference, the curve estimated from the Rutherford formula is also drawn in a broken curve-r. The deviation of the broken curve-g from the other curves is due to inaccuracies of the Gaussian approximation, wherein the upper bound of angular range of the single scattering formula corresponding to the nuclear form factor used in the approximation exceeds the geometrical limit of π for electrons of energy less than a few of ten MeV where the nuclear form factor is not effective. Accordingly we correct the inaccuracy of Gaussian approximation by the ratio of the mean square angle μ_2 of the single scattering formula between the Mott formula and the Gaussian approximation. The corrected Molière one is given by a chain curve-e (hereafter referred as EGS-like) in Fig. 1. In the same figure the measured data of $E[\langle\theta^2\rangle]^{1/2}$ for Kamiokande detector and IMB detector at the events of SN1987A (Bratton et al., 1988: Hirata et al., 1988a) show small values of about a half of the theoretical predictions of curves-m, -r and -e. This discrepancy is not due to different values of the threshold energy. Because modification of the calculated E[$\langle\theta^2\rangle$]$^{1/2}$ values introducing the low energy cut at 1, 2, 4, and 8 MeV under Gaussian approximation cannot agree with the measured E[$\langle\theta^2\rangle$]$^{1/2}$ values as shown by dotted lines in the figure. This behaviours may be attributed to the false measuements for E[$\langle\theta^2\rangle$]$^{1/2}$ of low energy electrons revealing large deflection angles in the water Cherenkov detector. The electron recoiled by ^{8}B neutrino radiates a certain number of Cherenkov photons (about 200 photons per 1 cm of water) in about 42 degrees from the direction of electron passing through water. The radiated photons are projected forming a shape of ellipse-like ring on a plane of photomultipliers. But such low energy electron suffers large deflection angles at few cases within their passages, in the cases there exits the possibility that the radiated photons are projected onto a different ellipse-like ring separated from other rings formed by electrons of smaller scattering angles. So the rings in large deflected angles are thinner and/or disappeared. Accordingly the evaluation of $E[\langle\theta^2\rangle]^{1/2}$ by the water Cherenkov detector may be favor to the smaller values. The dis-

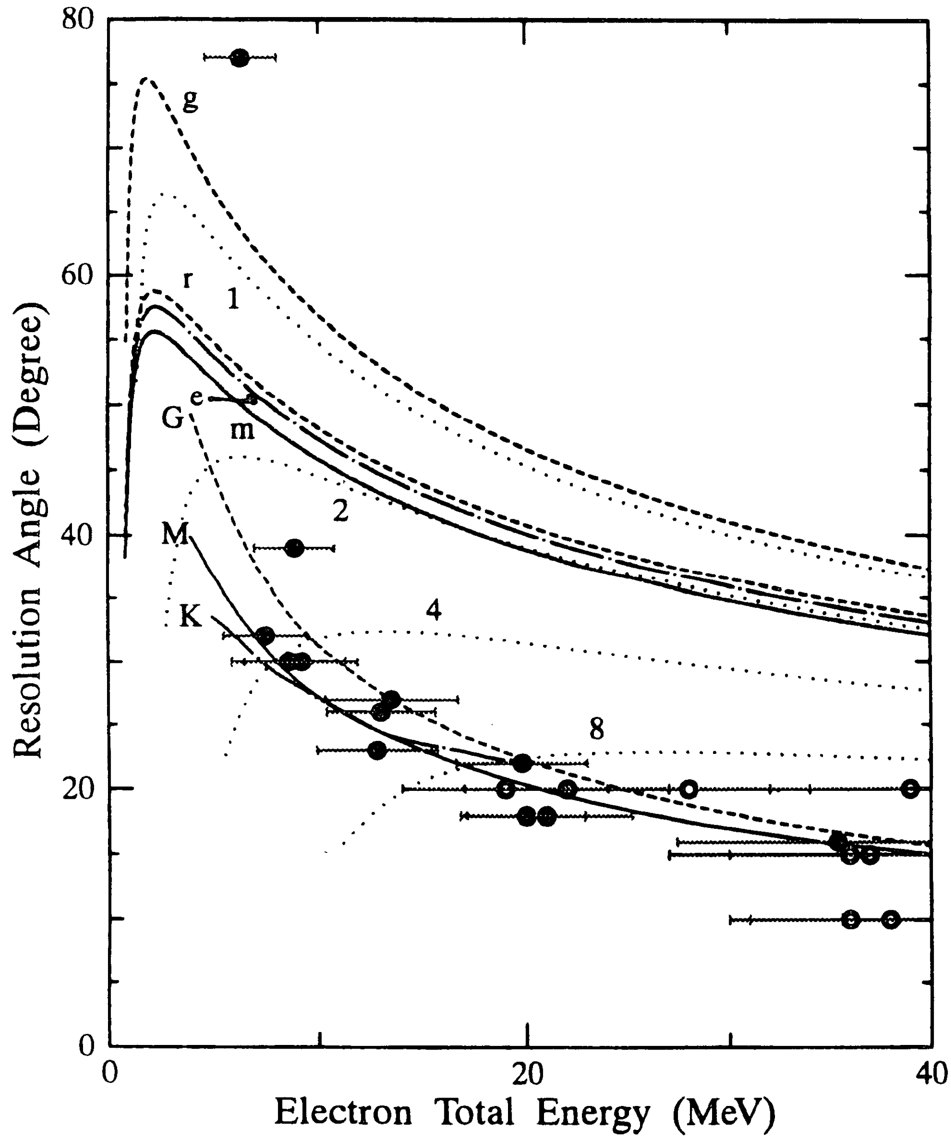

Figure 1: Comparisons of various calculated $E[\langle\theta^2\rangle]^{1/2}$ values with the measured values of electrons detected in the neutrino burst of SN1987A.

- a broken curve-g: Gaussian approximation formula (Williams),
- a broken curve-r: Rutherford formula,
- a chain curve-e: EGS-like,
- a solid curve-m: Mott formula.
- a solid curve-K: Kamiokande derivation by Nakahata.
- a broken curve-G: the Gaussian approximation with rapid decreasing of detection efficiency (reduction function, see Fig. 1).
- a solid curve-M: Our semi-emiprical formula (Kamiokande derivation by Hirata after gain change almost agrees with this curve).
- dotted line-1, -2, -4, -8: $E[\langle\theta^2\rangle]^{1/2}$ with different threshold energy of 1 MeV, 2 MeV, 4 MeV and 8 MeV, respectively.
- black circles (•): Kamiokande data, circles (○) : IMB data.

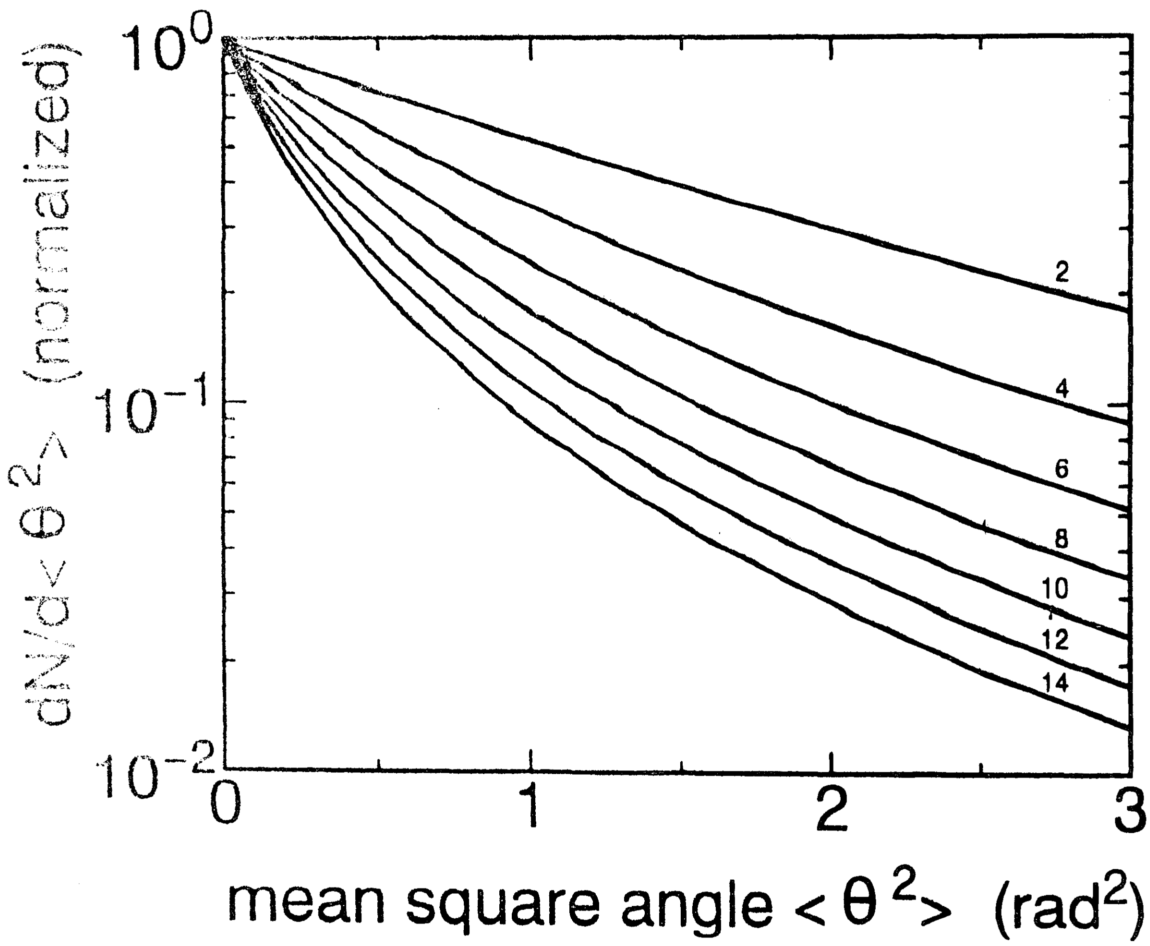

Figure 2: Dependences of $dN/d\langle\theta^2\rangle$ on $\langle\theta^2\rangle$ in various incident energies of electrons. Solid curves show cases with incident energies of 2, 4, 6, 8, 10, 12, and 14 MeV.

crepancy between the evaluated and calculated values for $E[\langle\theta^2\rangle]^{1/2}$ being smaller with decreasing electron energy as seen from Fig. 1 may be understandable by the above assumption. Thus we use the numbers of emitted photons decreasing almost exponentially with increasing $\langle\theta^2\rangle$ as shown in Fig. 2. Then the Mott and EGS-like resolution angle $E[\langle\theta^2\rangle]^{1/2}$ with the reduction function are shown by a broken curve-G and a solid curve-M in Fig.2, respectively. These distributions can explain the measured data of SN1987A to be in good agreement over the wide energy range. We emphasize that the measured data cannot be explained except by the rapid exponential decrease of detection efficiency with increasing scattering angle for the detector. The distribution is based only on the above assumption. However, the resolution angle $E[\langle\theta^2\rangle]^{1/2}$ obtained by the Kamiokande Monte Carlo calculations showing by a chain curve-K in Fig. 1 is almost in agreement with our curve-M. How do they get the resolution curve specific to their detector fitting to the measured data in SN1987A by their Monte Carlo calculations using EGS4 code?

3 Comparison of respective $\cos\theta_{sun}$ distribution

Substituting expressions of $E[\langle\theta^2\rangle]$ into eq. (1), we can obtain numerically the respective $\cos\theta_{sun}$ distributions of the neutrino flux in the Kamiokande detector based on the predicted electron energy spectrum from ^{8}B neutrinos using the SSM prediction, after taking into account the trigger efficiency and the energy resolution in the detector. Those calculated $\cos\theta_{sun}$ distributions in which the total flux of the ν_e-e^- scattering process is normalized to unity, are shown in Fig. 3: Mott formula with the reduction function (Mott with r.f.; solid curve) and without the reduction function (Mott without r.f.) are shown together with Kamiokande-EGS (o) in Fukuda et al., 1996. The distributions of Rutherford, Williams, and EGS-like formulae are almost same as the Mott one despite they are not shown. But, the Kamiokande-EGS distribution appears close to Mott distribution with the reduction function near $\cos\theta_{sun} \sim 0.95 - 0.7$ and to the same distribution without the reduction function over $\cos\theta_{sun} \sim 0.4$. Such behaviour is inconsistent with itself, because the Kamiokande-EGS is due to depending on the original Molière formula.

When using the maximum likelihood method as done for the Kamiokande analysis by use of the data (1036 days) in Fukui *et. al.*, 1996, we obtain the value for the observed $data/SSM_{BP92}$ from several $\cos\theta_{sun}$ distributions derived the above discussed scattering theories. The values are given in Table 1. Each error in the value is obtained by the likelihood ratio test with a confidence interval of 90%. All $\cos\theta_{sun}$ distributions are tested with each goodness-of-fit for the signal data after removing backgrounds by using the Smirnov-Cramer-von Mises method, established the fittness with a significance level of 0.1. Accordingly the value for $data/SSM$ has ambiguity of at least about 10% (except EGS-like case) moving downward without the statistical and systematic errors. The Mott formula without the reduction function (see Fig. 1) derived the value of 0.51 for $data/SSM_{BP92}$ by the maximum likelihood method. However, the significance is much less than 0.001, because the expected $\cos\theta_{sun}$ distribution has a different shape from the observed angular distribution of measured data so that the maximum likelihood method cannot be applied for such case. When using the same formula by the χ-squared method, the value for $data/SSM$ gives about 0.43, but the significance is again less than 0.001. Accordingly we can see the formula without the reduction function cannot give any correct value for the Kamiokande $data/SSM$ by the maximum likelihood method. Such the discrepancy between the measured values and the theoretical ones for $E[\langle\theta^2\rangle]^{1/2}$ specific to the Cherenkov water detector has to be resolved for the further experiments.

For getting the definite value of ^{8}B neutrinos flux, the further study in Super Kamiokande by use of a portable electron linac machine is necessary to resolve the discrepancy between the experimental and theoretical rms scattering angles of around 10 MeV region for the water Cherenkov detector. Observational distinction between the ^{8}B neutrinos and the background events produced by neutrons is also a difficult problem. This shows still insufficient 4π solid-angle anticounter system and the dead time of 20 sec of prompt muons in the Kamiokande detector that can give serious mistaken observation for atmospheric neutrino flux and for evidence of neutrino oscillations. The problem should be resolved for carrying through the Super Kamiokande experiment.

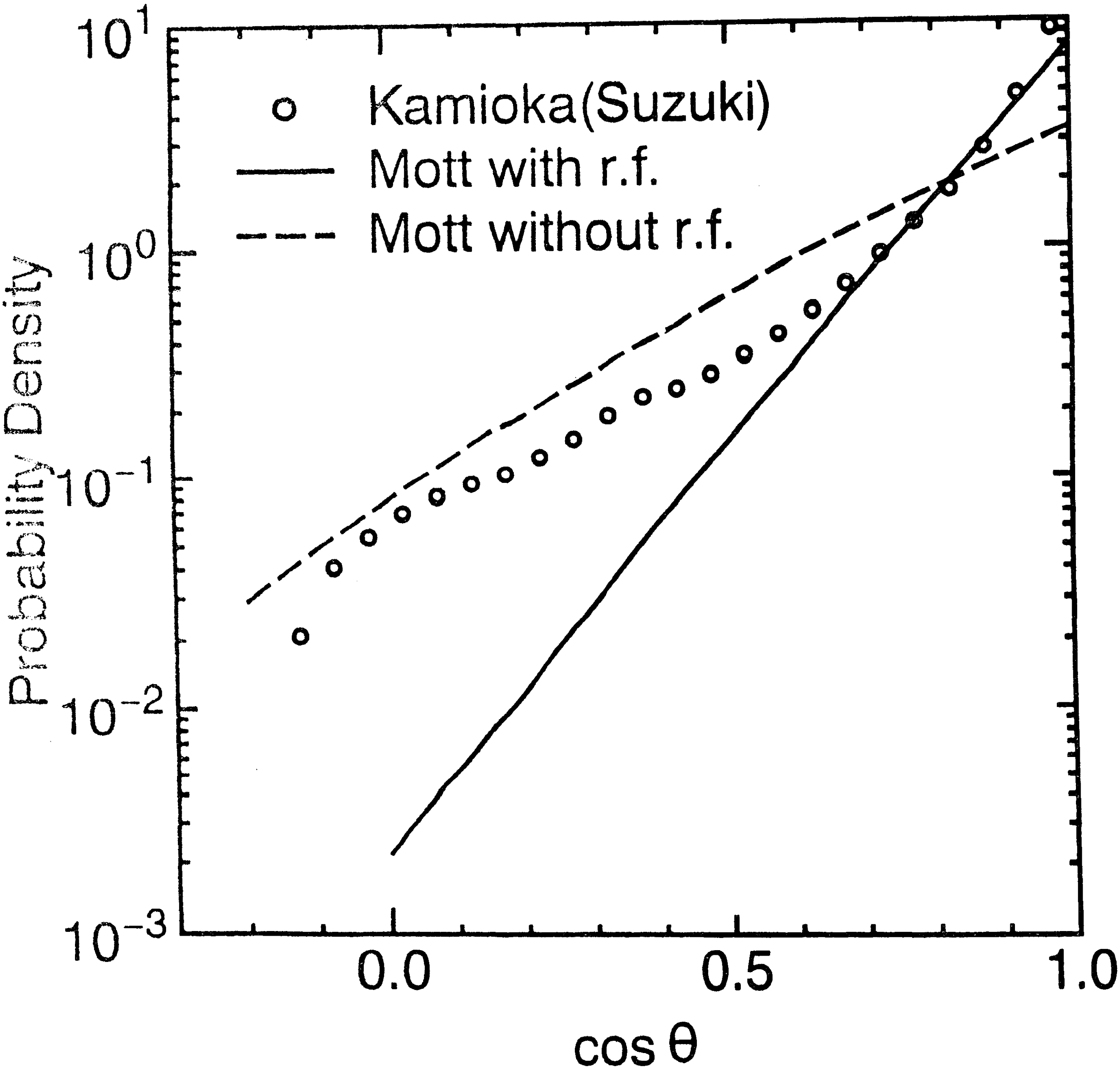

Figure 3: Comparisons of $\cos\theta_{sun}$ distributions obtained from various $E[\langle\theta^2\rangle]$ values.

- solid curve: our semi-emprical Mott formula with reduction function.
- chain curve: EGS-like model.
- dotted curve: Mott formula without reduction function.
- ○: expected Kamiokande-EGS4.

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