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論文内容要旨

The Sun radiates large amounts of energy, primarily released as photons, which slowly diffuse their way to the surface of the Sun. Generally speaking, solar photons bring the surface information of the Sun, almost all of the interior information is lost due to repeated interactions with various particles along their path to the surface of the Sun. On the other hand, neutrinos created in the core of the Sun can reach us from otherwise inaccessible regions where photons are trapped. Neutrinos only interact weakly with matter and their cross sections are very small. Neutrinos can therefore be used to look inside stars and examine directly physical processes that occur only in stellar interiors. We can study the interior of the Sun or the core of a collapsing star as it produces a supernova. Also, the study about neutrinos from the Sun provide us the important test for the theories of stellar evolution and structure.

The Standard Solar Model (SSM) attempts to describe the solar processes, but is constrained to our present day Sun. SSM predicts that the Sun is stable against gravitational collapse due to the power generated by a series of nuclear fusion reactions that produce the neutrinos in the process. In 1965, these neutrinos (so-called solar neutrinos) were detected by R.Davis in the Homestake mine. This experiment only measured half of the predicted SSM flux. Other solar experiments like Kamiokande (Kamioka Nucleon Decay Experiment) also yielded result in conflict with the SSM prediction. This disagreement between theory and observation is known as the Solar Neutrino Problem. The most plausible solution for this anomaly is neutrino oscillation, which was first suggested by Maki, Nakagawa, and Sakata in 1962. Neutrino oscillation describes neutrino flavor changing while the neutrino propagates, similar to what is observed in the quark sector. Massless particles cannot change their flavor, thus the neutrinos that undergo oscillation must be massive. An additional effect happens in the Sun, the neutrino weakly interacts with other particles and the behavior of the oscillation changes. This effect is called the MSW effect which was described by Mikheyev, Smirnov, and Wolfenstein. The observed solar neutrino spectrum is expected to be distorted due to the transition of vacuum to matter enhanced neutrino oscillation. From 1998 onward, two experiments, Super-Kamiokande (SK) and SNO (Sudbury Neutrino Observatory), which were founded to study the unknown properties of neutrinos, gave a lot of suggestive results. These experiments use Cherenkov light to detect the neutrino events. Their energy threshold is about 5 MeV, so ^{8}B solar neutrino is dominant in the detected solar neutrinos. SK measured the atmospheric neutrino anomaly and reported the first evidence for neutrino oscillation. The SNO group observed neutrino flavor transformation from neutral-current interaction (NC) and confirmed that the total flux of all neutrino types is consistent with the theoretical prediction of SSM. In 2002, KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector) reported the first result, which revealed a significant deficit of electron anti-neutrinos from distant power reactors and suggested the LMA-MSW solution which does describe "solar neutrino solution of the neutrino oscillation". The successive result of KamLAND showed evidence of spectral distortion of the reactor neutrinos. From these results of solar, atmospheric, and reactor neutrinos, the neutrino oscillation is confirmed. However, the spectral distortion of ^{8}B solar neutrino caused by the transition of vacuum to matter enhanced neutrino oscillation is not observed yet.

The study of neutrino oscillation in the (Δm^2, $\sin^2\theta$) parameter space has been done by various solar neutrino experiments, and it covers only the range of $0 < \theta < \pi/4$ (called the light side) with positive Δm^2. Indeed, some of the solutions to the solar neutrino problem extend to the other half of the parameter space $\pi/4 < \theta < \pi/2$ (called the dark side), and hence it is phenomenologically necessary to include both halves of the parameter space. However, the dark side has been neglected since it is impossible to obtain ν_e survival probabilities less than 1/2 without the MSW effect. Indeed, the data from the Homestake experiment, a solar neutrino experiment with radiochemical material, is about 1/3 of the SSM prediction, and could have been an argument for dropping the dark side in the MSW region, which corresponds to $10^{-8} < \Delta m^2 < 10^{-3}$ eV^2. However, some people question the SSM and/or Homestake experiment. The direct measurement of the transition of vacuum to matter enhanced neutrino oscillation is a good test for the dark side of the solar neutrino parameter space.

This work presents the first measurement of the ^{8}B solar neutrino flux with 3.5 and 5.5 MeV energy threshold with KamLAND, which is composed of a 1,000 tons liquid scintillator. It is important to estimate backgrounds accurately in order to observe ^{8}B solar neutrinos, since the detection method of solar neutrinos is an electron-neutrino elastic scattering. In this work, backgrounds are estimated in detail. Although ^{8}B solar neutrino observation has been done by SK and SNO, only one other scintillation detector, Borexino, has done any ^{8}B solar neutrino measurements. Firstly, this work confirms ^{8}B solar neutrino observation at energy threshold of 5.5 MeV. The ^{8}B solar neutrino flux was measured with an energy threshold of 5.5 MeV with 982 days of livetime corresponding to 126 kton-days exposure. The observed flux is $1.426^{+0.459}_{-0.448} \times 10^{6}\ cm^{-2}\ sec^{-1}$. Furthermore, this work is concerned with the transition ot vacuum to matter enhanced neutrino oscillation by means of ^{8}B solar neutrino observation at energy threshold of 3.5 MeV. Due to the scintillation purification, 62.5 days of livetime (8.8 kton-days exposure) was available with a lower energy threshold of 3.5 MeV, providing an upper flux limit of $2.47 \times 10^{6}\ cm^{-2}\ sec^{-1}$.

論文審査の結果の要旨

本論文は、液体シンチレータを使ってB8太陽ニュートリノの高エネルギー成分を観測するとともに、ニュートリノ振動の物質効果検証に有効な低エネルギー領域のバックグラウンド削減手法を開発したものである。

太陽中心の核融合反応は、ニュートリノ観測で直接検証することができる。これまで水チェレンコフ型の装置では、高エネルギー成分のみが観測されていたが、大光量の液体シンチレータで観測しきい値を低減することで、ニュートリノ振動の物質効果によるエネルギースペクトルの歪みの直接検証が期待できる。しかし、水チェレンコフ型と違い、方向感度のない液体シンチレータでは大幅なバックグラウンド低減とバックグラウンドの詳細な理解が必須となる。

本論文は、極低バックグラウンドの液体シンチレータを有するカムランド検出器を用い、5.5MeV以上で問題となる宇宙線ミューオンによる原子核破砕反応や壁面からのγ線によるバックグラウンドの評価を精緻に行った。特に、原子核破砕反応の評価では、先行する観測が見過ごしていたバックグラウンドも発見し、25%ものフラックスの修正が必要であることを見いだした。また、より低エネルギーの3.5MeV以上で支配的となるTl208由来のバックグラウンドに対しては、親核のBi212からのα線をタグすることで解析的な除去が可能なことに着目し、見た目のエネルギーが400keVと非常に低いα線を観測するため、液体シンチレータの蒸留および窒素パージによる純化を行い、大幅なバックグラウンド低減に成功した。純化以前では126 kton-daysのデータに対して観測しきい値5.5MeVの解析を行い、ニュートリノ振動がない場合のスペクトルの形を仮定したB8太陽ニュートリノのフラックスとして、$1.78^{+0.48}_{\ 0.46}\times 10^{6}/cm^{2}/sec$（レート解析）を得た。これは、標準太陽模型（BP05GS98）の予測値の0.31倍にすぎず、その結果、5σ以上の有意さで太陽ニュートリノ欠損を検証できた。蒸留後においては、8.8 kton-daysのデータに対して観測しきい値3.5 MeVの解析を可能にし、4.1σの有意さで太陽ニュートリノ欠損を確認した。

本論文が示す、液体シンチレータを使ったB8太陽ニュートリノの観測およびエネルギーしきい値低減の手法は、ニュートリノ天文学の発展に大きく寄与するものであり、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって岐部佳朗提出の博士論文は博士（理学）の学位論文として合格と認める。