

Hunting Massive Majoron Emission in Neutrinoless Double-Beta Decay of ^{136}Xe with KamLAND-Zen

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URL	http://hdl.handle.net/10097/00135423

論文内容要旨

(NO. 1)

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学位論文の 題目	Hunting Massive Majoron Emission in Neutrinoless Double-Beta Decay of ^{136}Xe with KamLAND-Zen 800 (KamLAND-Zen による ^{136}Xe のニュートリノを伴 わない二重ベータ崩壊における有質量マヨロン放出 過程の探索)		

At present, the Standard Model has achieved great success as a theory for describing elementary particle physics because of its agreement with experiments. However, in recent years, several new experimental results have called for a revision of the Standard Model. For example, the discovery of neutrino oscillations showed that the mass of neutrinos, which had been postulated to be zero, has a finite value. This posed a new mystery to the enigmatic elementary particle neutrino, which is the Majorana particle. A Majorana particle is a particle whose antiparticle is itself. Only neutrinos, which are massive fermion with no electric charge, are allowed to have the Majorana nature. Another interesting fact is the evidence of dark matter. The universe and gravitational lensing observations have confirmed the existence of unobservable and unknown matter that is approximately 30 times larger than the baryonic matter we normally perceive. The Standard Model cannot explain these phenomena, and new evidence is expected to be presented by experiments.

The only realistic way to show the Majorana nature is to observe neutrinoless double-beta decay ($0\nu\beta\beta$), which has never been found yet. Dark matter has also been searched for by many experiments using various techniques but has not been found at present. One possibility is that the new particle majoron, which is closely related to both, may play a fascinating role. Majorons, denoted by J , are hypothetical Nambu-Goldstone bosons associated with spontaneous lepton number violation. If the $0\nu\beta\beta$ occurs, it violates the lepton number by two units. The majoron emission in $0\nu\beta\beta$ ($0\nu\beta\beta J$) is allowed in certain theories. Usually, majoron is massless, but it can become a pseudo-Nambu-Goldstone boson with finite mass if majoron has mass. The massive majoron can behave as dark matter based on the freeze-in mechanism. Of course, massive majoron emission in $0\nu\beta\beta$ can be assumed. This means that the $0\nu\beta\beta$ search will have new significance. KamLAND-Zen 800 is an experiment to search for the $0\nu\beta\beta$ with ^{136}Xe .

It has been observing with high sensitivity on the strengths of a low background environment and a large target mass of 745-kg xen on gas enriched 91% ^{136}Xe . The observation started in January 2019, and the 744.6-days running time (523.4-days livetime) is available for analysis. This dissertation reports the improvement of massless $0\nu\beta\beta J$ search (for spectral index $n=1$) and first search for massive $0\nu\beta\beta J$. This work obtains the most stringent limit that is massless $0\nu\beta\beta J$ half-life of $T_{0\nu\beta\beta J}^{1/2} > 5.6 \times 10^{24}$ yr (90% C.L.) corresponding to the neutrino-majoron coupling constant of $\langle g_{ee} \rangle < (3.9 - 8.0) \times 10^{-6}$. The search for massive majoron emissions has been reported for the first in the world by this work. In the region below ~ 0.8 MeV of the majoron mass, we have set a new limit on the neutrino-majoron coupling constant beyond the existing exclusion region by SN1987A.

論文目次

Chapter	1	Introduction	1
Chapter	2	Physics	4
	2.1	Dark Matter	4
		2.1.1 Evidence for Dark Matter	4
		2.1.2 Standard Cosmological Model	10
		2.1.3 Dark Matter Candidates	13
		2.1.4 Detection Method and Experiments	15
	2.2	Neutrino	19
		2.2.1 Dirac and Majorana neutrinos	19
		2.2.2 Origin of neutrino mass	21
	2.3	Double-Beta Decay	22
		2.3.1 Double-Beta Decay with Neutrino Emission	23
		2.3.2 Neutrinoless Double-Beta Decay	24
		2.3.3 Experiments	26
	2.4	Majoron	26
		2.4.1 Massive Majorons	26
		2.4.2 Massive Majoron as Dark Matter	27
		2.4.3 Majoron emission in Neutrinoless Double-Beta Decay	28
		2.4.4 Experiments for Majoron search	32
Chapter	3	KamLAND-Zen Experiment	36
	3.1	Overview	36
	3.2	Detector	37
		3.2.1 Liquid Scintillator	38
		3.2.2 PMT	39
		3.2.3 Inner Detector	40
		3.2.4 Outer Detector	41
		3.2.5 Xenon Loaded Liquid Scintillator	41
		3.2.6 Inner-Balloon	42
		3.2.7 Inner-Balloon Supporter	43
	3.3	Data Acquisition System	44
		3.3.1 KamDAQ	45
		3.3.2 MoGDAQ	46
		3.3.3 Slow Detector Condition Monitor	47
Chapter	4	Work on KamLAND-Zen 800 start-up	48
	4.1	Inner-Balloon Production	48
		4.1.1 History	49
		4.1.2 Environments of production	50
		4.1.3 Inner-Balloon Fabrication	51
		4.1.4 Packing and Shipping for Kamioka	56
	4.2	Inner-Balloon Supporter Production	57
		4.2.1 Preparing for Assembling	57
		4.2.1 Assembling	57
	4.3	Inner-Balloon Installation	62
	4.4	Xenon Loaded Liquid Scintillator Filling	63
		4.4.1 LS Distillation	63
		4.4.2 Xenon Dissolving	65
		4.4.3 Detector Condition	67
Chapter	5	Data Handling	68
	5.1	Analysis Framework	68
	5.2	Event Reconstruction	69
		5.2.1 PMT Waveform Analysis	70
		5.2.2 PMT Data Correction	71
		5.2.3 Vertex Reconstruction	79
		5.2.4 Energy Reconstruction	80
		5.2.5 Muon Reconstruction	82
		5.2.6 Neutron Reconstruction	83
	5.3	Event Selection	84

		5.3.1 Bad Data Rejection	85
		5.3.2 Unphysical Events Rejection	86
		5.3.3 Background Events Rejection	86
		5.3.4 Selected Events	95
		5.3.5 Livetime	97
Chapter	6	Background Model	98
	6.1	MC simulation	98
	6.2	Natural Radioactivities	100
		6.2.1 ^{238}U series	100
		6.2.2 ^{232}Th series	100
		6.2.3 Others	101
	6.3	Spallation Backgrounds	102
		6.3.1 Light isotope	102
		6.3.2 Heavy isotope	104
	6.4	Solar Neutrino	107
	6.5	External Background	108
	6.6	Potential Background	108
Chapter	7	Analysis	109
	7.1	Strategy	109
	7.2	Condition	110
		7.2.1 Target Amount	110
		7.2.2 Data-set	111
		7.2.3 Uncertainties	111
	7.3	Physics Search	112
		7.3.1 Fitting Method	112
		7.3.2 Fitting Parameters	113
		7.3.3 Fitting Result	116
	7.4	Discussion	120
		7.4.1 Constraints	120
		7.4.2 Combined constraint on the half-life of massless $0\nu\beta\beta$ of ^{136}Xe	121
		7.4.3 Comparison of results	122
		7.4.4 Future Prospects	124
Chapter	8	Conclusion	126
Appendix	A	Fitting result for massive $0\nu\beta\beta$	127
Appendix	B	Energy spectra for massive $0\nu\beta\beta$ best-fit	133
Bibliography			142

別 紙

論文審査の結果の要旨

本論文は、 ^{136}Xe の二重ベータ崩壊でのマヨロン放出を探索したものである。キセノン量増大とバックグラウンド事象の低減により、質量 0 のマヨロンの結合定数に対する最も厳しい実験的制限とともに、有質量マヨロンに対する初めての実験的制限を与えた。

レプトン数を破るニュートリノのマヨラナ質量項に対して、バリオン数-レプトン数を大局的な対称性とし、その自発的対称性の破れがこの破れの原因と考え、新たな南部・ゴールドストーンボソンが生じる。このボソンはマヨロンと呼ばれ、一般にニュートリノと結合する。マヨロンの導入は、超新星爆発でのエネルギー放出や、超新星核の状態方程式に修正をもたらすことから、天文学的な制限がある。一方実験的には、ニュートリノを伴わない二重ベータ崩壊においてニュートリノとの結合でマヨロンが生じる事象を探索することで、結合定数を調べることができる。理論的には暗黒物質の候補にもなる有質量マヨロンも可能なため、質量 0 を仮定したこれまでの探索に加え、初めて有質量の場合の探索が行われた。これらの探索では大量の二重ベータ崩壊核を用意し、マヨロン放出に伴うエネルギースペクトルの歪みを低バックグラウンドで詳細に調べる必要がある。本論文では、スーパークリーンルームでの慎重な製作を通して放射性不純物量を 10 分の 1 に低減するとともに、キセノン量を 745kg に倍増し、大幅な探索感度向上を実現した。また、宇宙線起源のバックグラウンドの理解を進め、測定装置特性の時間変化を緻密に補正することで、系統誤差も抑えられている。その結果、カムランド禅実験の全データを用いた統合解析では、質量 0 のマヨロンへの崩壊に対して半減期 5.9×10^{24} 年以上 (90%信頼度)、電子ニュートリノとの結合定数換算で $\langle g_{ee} \rangle < (3.8 - 7.9) \times 10^{-6}$ (90%信頼度、制限の範囲は核行列要素の不定性による) という実験的探索で最も厳しい制限を与えた。また、有質量の場合にはマヨロン質量 0.9MeV 以下でこれまで未踏のパラメータに排除領域を広げた。

本論文は、高度な解析によって最も厳しい 0 質量マヨロンへの実験的制限を与えるとともに、有質量マヨロンに対しても初めて制限を与えた。これらの成果は、自立して研究活動を行うのに必要な高度な研究能力と学識を有することを示しており、したがって、亀井雄人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。