CP非対称性の破れと物質反物質非対称性問題、発展と展望

Physics 2008

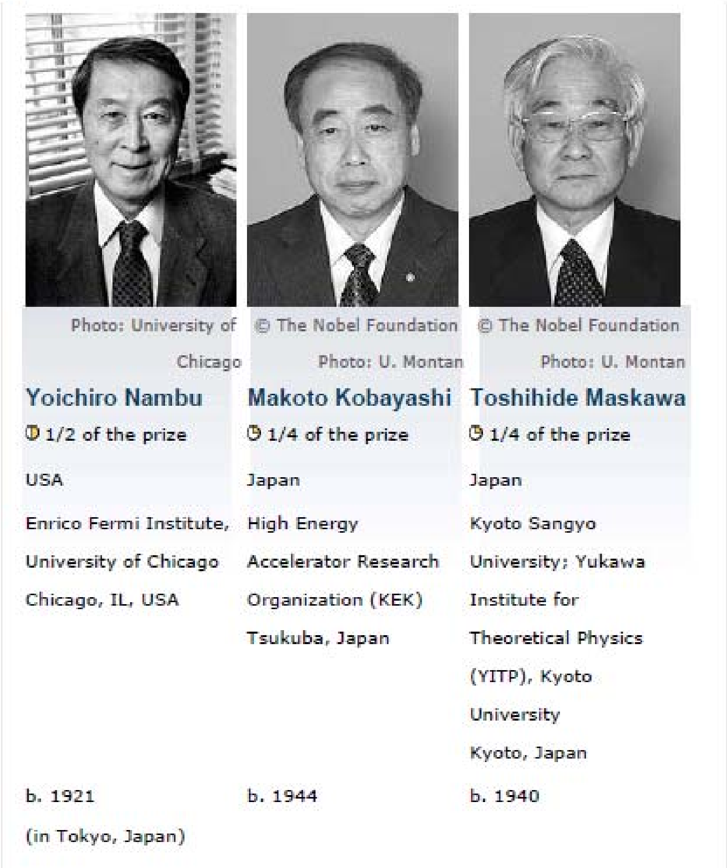
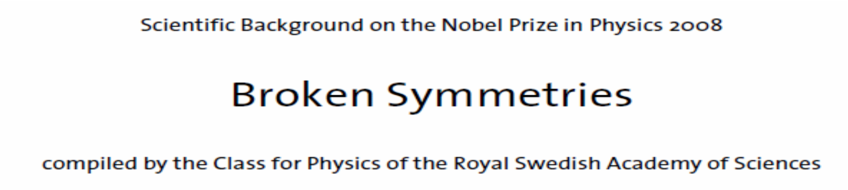


Photo: University of Chicago	© The Nobel Foundation Photo: U. Montan	© The Nobel Foundation Photo: U. Montan
Yoichiro Nambu	**Makoto Kobayashi**	**Toshihide Maskawa**
1/2 of the prize	1/4 of the prize	1/4 of the prize
USA	Japan	Japan
Enrico Fermi Institute, University of Chicago Chicago, IL, USA	High Energy Accelerator Research Organization (KEK) Tsukuba, Japan	Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University Kyoto, Japan
b. 1921 (in Tokyo, Japan)	b. 1944	b. 1940

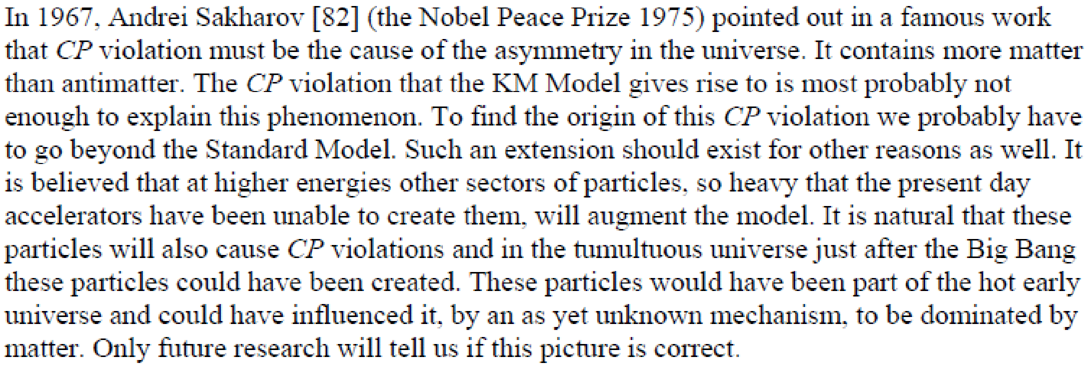


Scientific Background on the Nobel Prize in Physics 2008

Broken Symmetries

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

受賞背景説明の最後に



In 1967, Andrei Sakharov [82] (the Nobel Peace Prize 1975) pointed out in a famous work that *CP* violation must be the cause of the asymmetry in the universe. It contains more matter than antimatter. The *CP* violation that the KM Model gives rise to is most probably not enough to explain this phenomenon. To find the origin of this *CP* violation we probably have to go beyond the Standard Model. Such an extension should exist for other reasons as well. It is believed that at higher energies other sectors of particles, so heavy that the present day accelerators have been unable to create them, will augment the model. It is natural that these particles will also cause *CP* violations and in the tumultuous universe just after the Big Bang these particles could have been created. These particles would have been part of the hot early universe and could have influenced it, by an as yet unknown mechanism, to be dominated by matter. Only future research will tell us if this picture is correct.

小史

- Sakharov , too early. Read by nobody
- M.Y, and others, 1978-1979

  GUT scenario

  Right time for physics beyond standard model
- Leptogenesis: A new twist made possible by subtle finite temperature effects of standard model
- Discovery of neutrino oscillation boosted idea of leptogenesis

私にとっての１９７８年

- 電弱統一、量子色力学が実験的に確実になり、標準理論が確立。
- 既に、標準理論をこえる大統一理論のアイディアが存在。
- 宇宙論は原子核物理までで十分と思われていた。
- 漸近的自由性が宇宙初期を簡単にする？

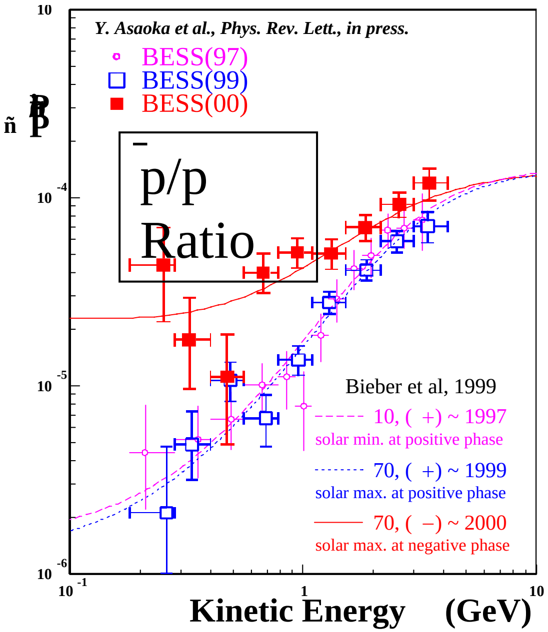
物質･反物質不均衡という事実はどれだけ確実か

- Observational evidence against symmetric cosmology

$$\frac{\overline{He}}{He} < 10^{-6}$$ near earth

low energy $\overline{p}$ spectrum

No evidence of γ from $\overline{N} + N \to \pi^0 + \cdots$


Y. Asaoka et al., Phys. Rev. Lett., in press.

- Theoretical problem with B-symmetric cosmology

$$\frac{n_B}{n_\gamma} = \frac{n_{\overline{B}}}{n_\gamma} = \frac{O[100]}{m_N m_{pl} \left\langle \sigma v \right\rangle_{N\overline{N}}} \approx 10^{-18} \qquad @T \approx \frac{m_N}{50}$$

much smaller than observed 10^{-10}

No working model of domain separation

Generation of B-asymmetry

- Key quantity

$$\left(\frac{n_B}{n_\gamma}\right)_{\text{after annihilation}} = O[1] \times \left(\frac{B-\overline{B}}{B+\overline{B}}\right)_{\text{before annihilation}}$$

Observation $\dfrac{n_B}{n_\gamma} = O\left[10^{-10}\right]$

imply 1 excess of B out of 10^{10} pairs

サハロフ3条件

in the early universe

Necessary ingredients

$\cancel{B}$ $\cancel{CP}$ *out of equilibrium*

Need of arrow of time

without suppression of inverse process,

$$\Delta B = (\Delta B)_{\rightarrow} + (\Delta B)_{\leftarrow} = 0$$

重い粒子崩壊の非平衡条件

$$X \to \overline{q}\overline{q}, ql$$

- One way decay, no inverse decay

$$H > \Gamma(= \alpha m_X)$$

$$H = \frac{1.6\sqrt{N}\,T^2}{m_{pl}} \qquad @T = m_X$$

Otherwise, Boltzmann suppression by $n_X \propto \exp(-m_X/T)$

Typically leading to

$$m_X > O[0.01]\alpha m_{pl} \approx 10^{15}GeV$$

Need for high unification scale

Reheating after inflation $T_{RH} > m_X$

CPの微妙さ：量子干渉効果

Baryon excess from a pair of particle and antiparticle process, e.g. X $\bar{X}$

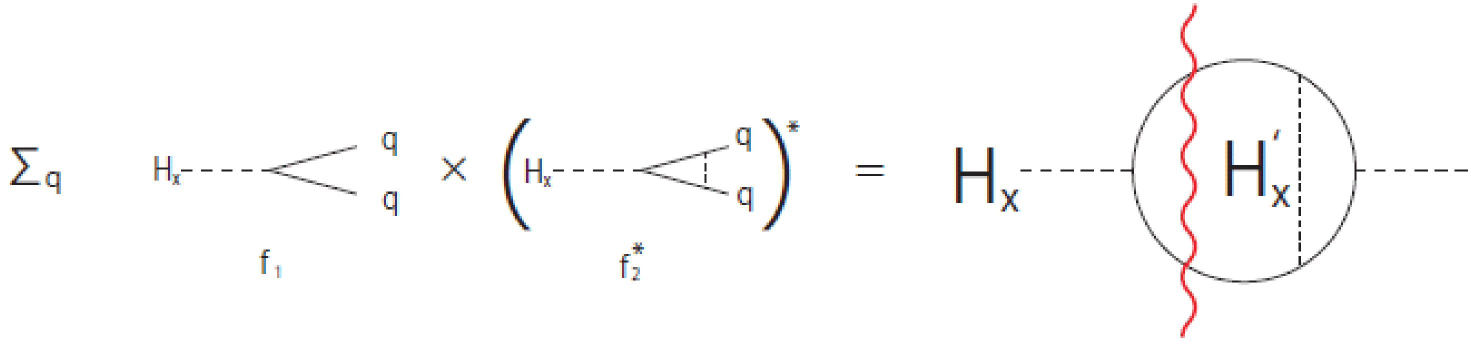
$$|g_1 f_1 + g_2 f_2 + \cdots|^2 - |g_1^* f_1 + g_2^* f_2 + \cdots|^2$$

$$= -4\,\mathrm{Im}(g_1 g_2^*)\,\mathrm{Im}(f_1 f_2^*) + \cdots$$

$\mathrm{Im}(g_1 g_2^*) \neq 0$ CP violation

$\mathrm{Im}(f_1 f_2^*) \neq 0$ Rescattering phase

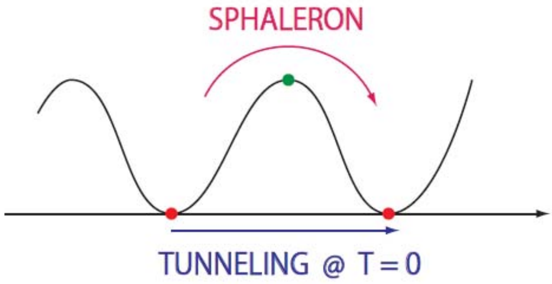
Interference computed by Landau-Cutkovsky rule



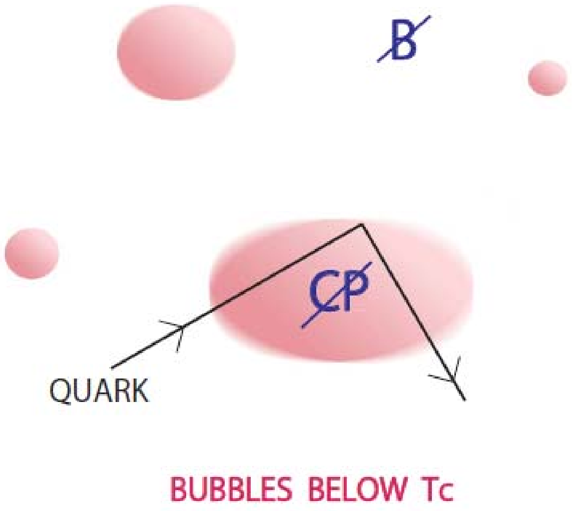
標準理論でのバリオン生成

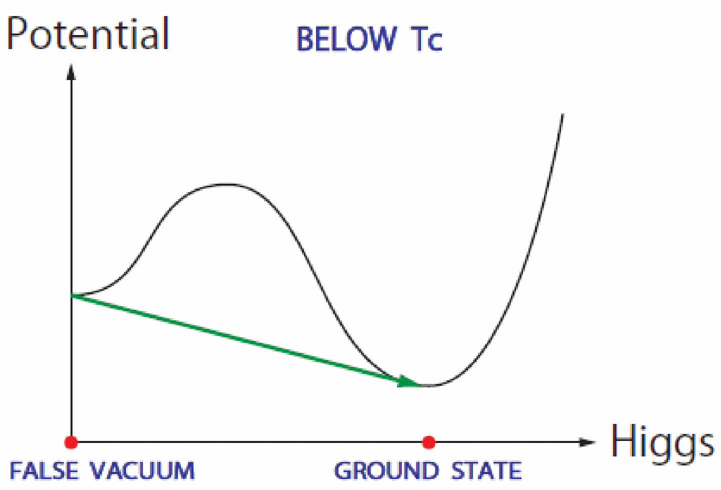
- $\cancel{B}$ unsuppressed $e^{-M_{sp}/T}$ at finite T

$$\gamma = o[1]\alpha_W{}^4 T \quad @ T >> M_{sp} \approx O[TeV]$$



- $\cancel{CP}$ KM phase
- Out of equilibrium: 1st order phase transition via bubble formation



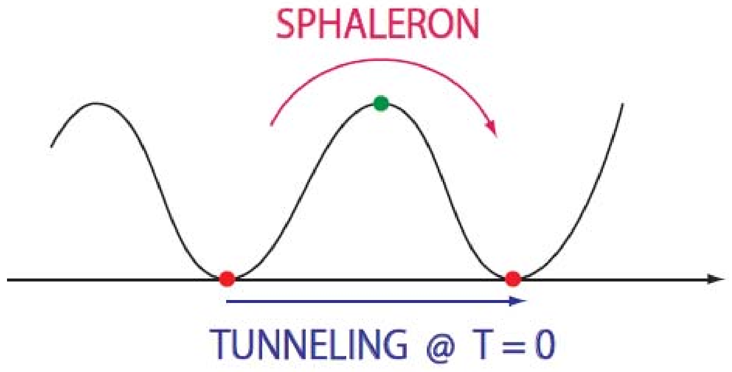


電弱バリオン生成の困難

- No strong 1st order phase transition due to experimental Higgs mass bound

- Magnitude too small $\frac{n_B}{n_\gamma} = o[10^{-21} - 10^{-25}]$

電弱バリオン非保存： B/L の平衡化



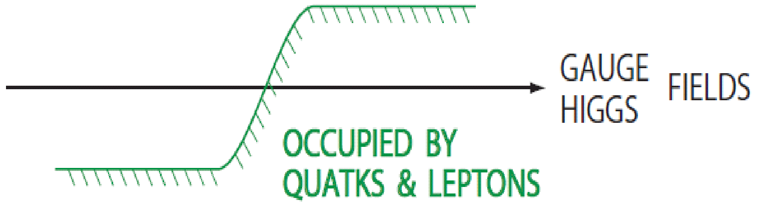
Electroweak baryon noncnoservation

suppressed at T=0 by e^{-137}

e^{-137}

enhanced at finite T by barrier crossing

Can destroy preexisting B and L while keeping B-L



Mechanism due to level crossing of fermions caused by nontrivial gauge and higgs configuration of sphaleron and alike

レプトジェネシスからバリオン転化

- L-genesis of amount ΔL first and electroweak conversion into B, via

$$B = -\frac{28}{79}\Delta L$$

For standard model of 3 generations

Interesting in view of possible connection to observed neutrino masses

Thermal L genesis

Fukugita-Yanagida

- Minimal extention of standard model with seesaw

$$N_R \rightarrow lH, \overline{l}\overline{H}$$

Right-handed Majorana decay

CP asymmetry with neutrino mass matrix

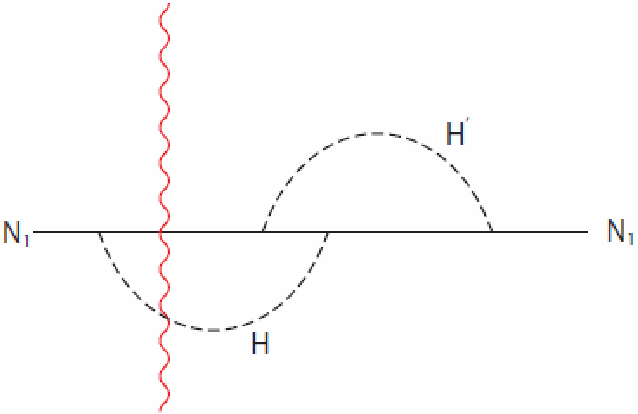
$$m_\nu = m_D M_N{}^{-1} m_D{}^T$$

$$\varepsilon_1 = \frac{3}{16\pi}\frac{M_1}{v^2}\frac{\mathrm{Im}(m_D{}^\dagger m_\nu m_D{}^*)_{11}}{(m_D{}^\dagger m_D)_{11}} = O\left[\frac{M_1\tilde{m}_\nu}{v^2}\delta\right]$$

Assuming mass hierarchy for 3 R-Majoranas N

$$\tilde{m}_\nu = \frac{(hh^+)_{11}}{M_1}v^2 = \frac{(m_D m_D{}^+)_{11}}{M_1}$$

$$\delta = \text{CP phase}$$



ニュートリノ質量値の衝撃:　宇宙の熱史への影響

With hierarchy of masses, dependence on 3 parameters　Giudice et al

$$\varepsilon_1, M_1, \tilde{m}_\nu$$

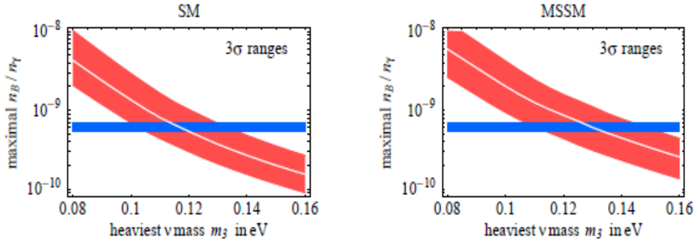


Figure 10: **Leptogenesis bound on neutrino masses**. *The plot shows the measured baryon asymmetry (horizontal line) compared with the maximal leptogenesis value as function of the heaviest neutrino mass m_3, renormalized at low energy. Error bars are at 3σ.*

- Connection to neutrino masses

$m_3 < 0.13 eV$　heaviest neutrino (WMAP,LSS 0.7eV)

$M_1 > 5 \cdot 10^8 GeV$　lightest R-neutrino

- Reheat temperature　$T_{RH} > M_1$

Gravitino problem: a possible nightmare both for GUT B- and L-genesis

- Superpartner of graviton

mass $m_{3/2} = O[TeV]$

lifetime $\Gamma = O[\frac{m_{3/2}^{\;3}}{m_{pl}^{\;2}}] = O[(10^5\,\mathrm{sec})^{-1}(\frac{m_{3/2}}{TeV})^3]$

- Usual estimate of gravitino abundance and constraint from nucleosynthesis, including hadronic decay

$$\frac{n_{3/2}}{s} = O[10^{-2}]\frac{T_{RH}}{m_{pl}}$$

$$T_{RH} < 10^6 - 10^8\,GeV$$

Possible to produce N_R, H_X ?

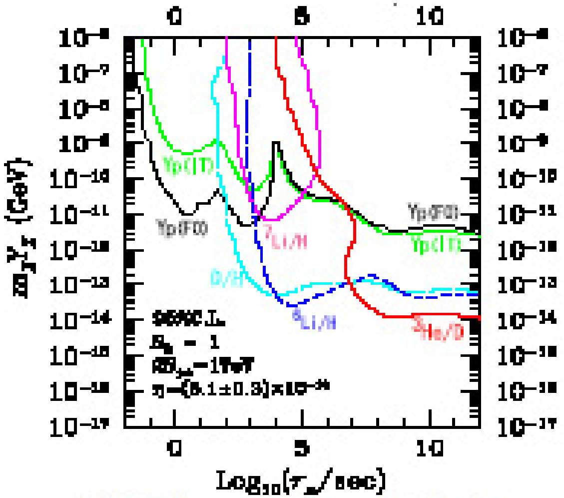


FIG. 2. Same as Fig. 1, except for $B_h = 1$.

種々の説

- 冷たい宇宙でのfield condensate

  Afleck-Dine 機構とその変形

- Electroweak TeV スケールでの新物理

レプトン生成かバリオン生成か

- グラヴィティーノ過剰生成問題があり、熱的生成のシナリオでは優劣つけがたい
- ニュートリノ振動＋シーソー理論は、レプトン生成に有利な印象

実験からのさらなるヒントが重要

- 大規模陽子崩壊実験

どのスケールを目標にするか　理論のインプットが必要か

新たな実験手法の開発

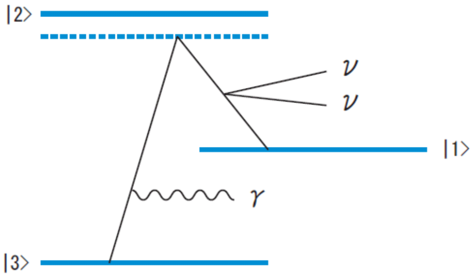
- レプトン数非保存

ニュートリノを伴わない2重ベータ崩壊

マヨラナニュートリノの検証　原子遷移

（30日のシンポジウム講演）

$$ {}^{Z}\mathrm{A} \rightarrow {}^{Z+2}\mathrm{A} + e^{-} + e^{-} $$



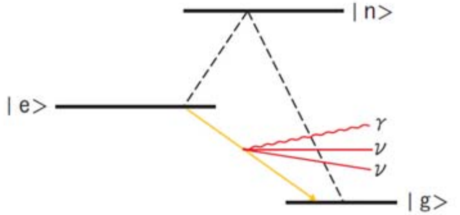
$|1\rangle \rightarrow |3\rangle + \gamma + \nu\ \nu$

励起原子マクロ超放射によるニュートリノ研究

- 準安定(ミリ秒以上)励起原子集団からのコヒーラント、光子＋ニュートリノ対超放射放出

$$|e\rangle \;\rightarrow\; |g\rangle + \gamma + \nu_i \nu_j$$

$$\text{Enhanced rate} \;\approx 10\,\text{Hz}\,\left(\frac{n}{10^{24}\text{cm}^{-3}}\right)^2 \frac{V}{\text{cm}^3}$$



| e> → | g> + γ + ν ν

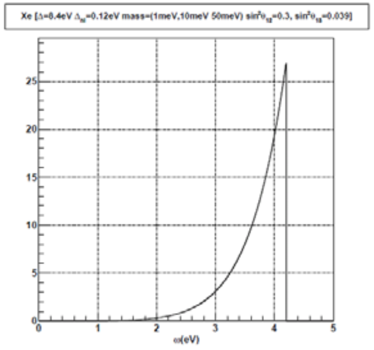
| e> → | g> + γ + γ

- 測定量
  1. 光子エネルギースペクトル
  2. 円偏光(パリティ非保存)

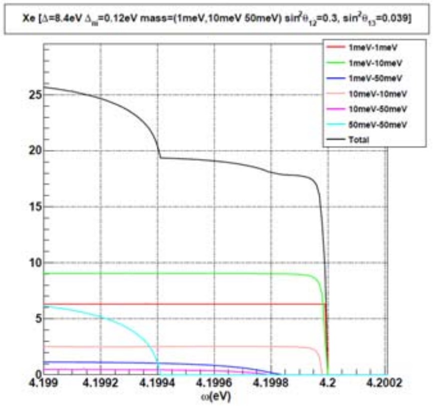
  質量に依る6閾値

  立ち上がり強度がθ_{13}角度依存

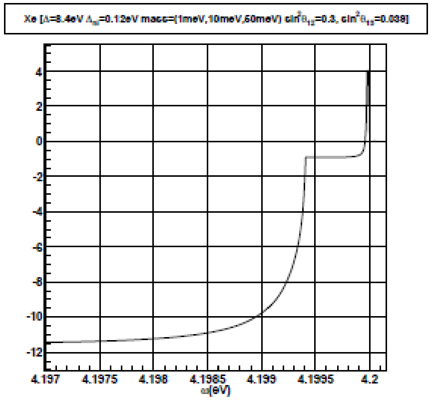
$$\omega_{ij} = \frac{\Delta}{2} - \frac{(m_i + m_j)^2}{2\Delta}$$



spectrum



Xeの場合



Parity odd quantity

マヨナラかディラックかの質量タイプ決定法

$$(i\partial_t - i\vec{\sigma}\cdot\vec{\nabla})\varphi = im\sigma_2\varphi^*$$

$$\varphi_{\vec{p},h}(x) = c(\vec{p},h)e^{-ip\cdot x}u(\vec{p},h) + c^\dagger(\vec{p},-h)e^{ip\cdot x}\sqrt{\frac{E_p+hp}{E_p-hp}}(-i\sigma_2)u^*(\vec{p},h)$$

$$u(\vec{p},h) = \frac{1}{2}\sqrt{\frac{E_p-hp}{pE_p(p+hp_3)}}\begin{pmatrix} p+hp_3 \\ h(p_1+ip_2) \end{pmatrix}$$

$$\sum_{h_1h_2}|j_M\cdot j^e|^2 = \sum_{h_1h_2}|j_D\cdot j^e|^2 + \delta_{ij}\frac{m_im_j}{2E_1E_2}\left(j_0^e(j_0^e)^\dagger - \vec{j}^e\cdot(\vec{j}^e)^\dagger\right)$$

同種フェルミオンの干渉効果

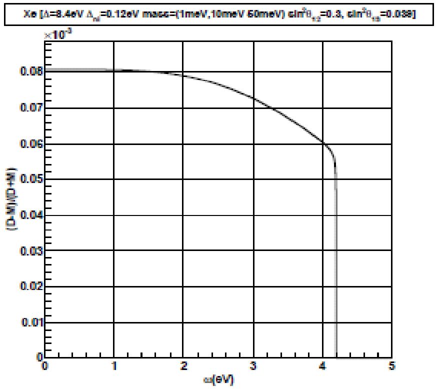


Figure 4: Majorana vs Dirac: expanded figure 3

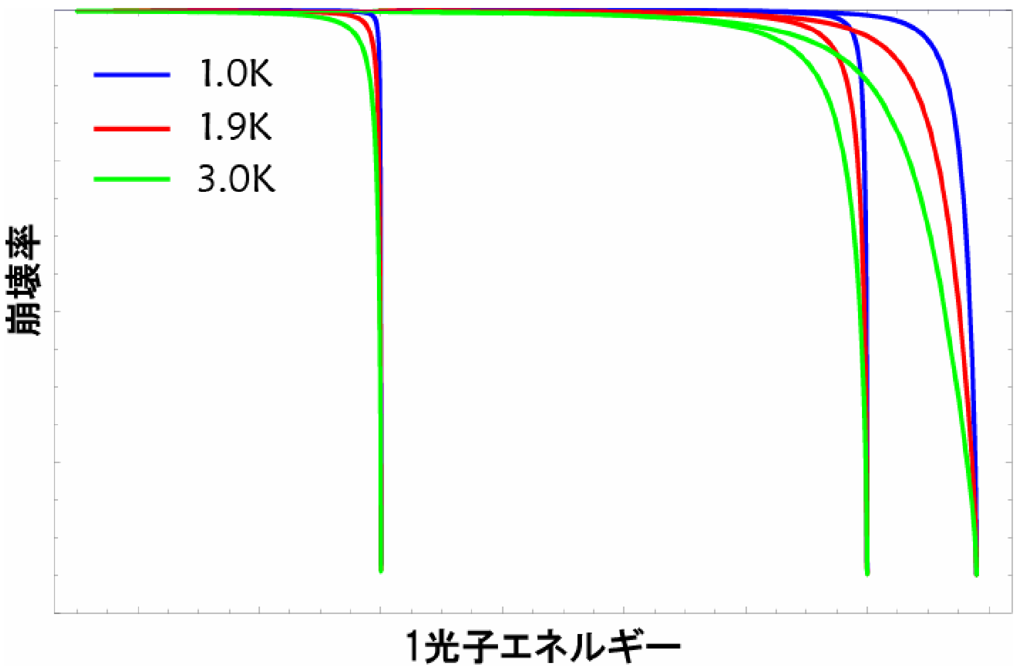
マヨラナとディラックの差

Xeの場合

宇宙背景ニュートリノ検出原理

パウリ排他効果による閾値付近のレート抑制

Relative rate



$$m_1 = 0.1\,,\ 1\,,\ 5\,meV$$

Photon energy

Threshold reduction 1/2x1/2 = 1/4

For m_1 < a few meV, temperature measurement is not difficult

素粒子標準理論では説明できない宇宙の謎

- バリオン非対称
- インフレーションの機構
- 暗黒物質の正体
- 暗黒エネルギー

今後ますます素粒子と宇宙の接触は深くなる

観測・実験と理論の共同作業が重要

まとめ

- 宇宙のバリオン非対称度の説明は標準模型をこえる新たな物理を要求する
- 小林・益川位相では説明困難
- バリオン生成かレプトン生成のどちらが先か、当面、ニュートリノ振動データとの関連でレプトジェネシスに焦点
- マヨラナ質量（レプトン数非保存）、陽子崩壊実験が鍵を握る