

2021年度

京都大学大学院理学研究科

D 3 発表会アブストラクト

(2022年2月9日)

物 理 学 第 二 分 野

# D3 発表会

日時:2022年2月9日(水) 9時～  
場所:ハイブリット形式  
発表時間:15分+5分(質問)

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3. Search for the  $nn\Lambda$  state via the  ${}^3\text{H}(e,e'K^+)X$  reaction at JLab 鈴木 一輝 (9:40)
4. 偏光  $\gamma$  線源を用いた時間-偏光メスバウアースペクトル測定法の研究 田嶋 寛介 (10:00)
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8. Algebraic tensor models: a potential spacetime interpretation of the canonical tensor model Obster Dennis (11:20)

# Rho resonance from lattice QCD: Technical improvement and its application

基礎物理学研究所 赤星友太郎

**Abstract** We investigate the rho resonance from lattice QCD. We propose a promising scheme to combine the all-to-all quark propagator and HAL QCD method. We succeed in determining the typical resonant structure using the inter-hadron potential from lattice QCD. Other applications of our scheme are also discussed.

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In this thesis, we introduce our challenges on the rho resonance study from lattice QCD. The HAL QCD method enables us to study hadron interactions from the spacetime dependence of correlation functions in lattice QCD, but there is a technical issue: the estimation of all-to-all quark propagators.

To overcome the difficulty, we first employ one of the typical methods to calculate all-to-all propagators called the hybrid method. We calculate  $I = 2, 1$  two-pion interactions and investigate their behaviors systematically[1,2]. We find that the computational cost to reduce noise contamination from the hybrid method is too high to perform large-scale simulations. After further investigations, we find that the combination of the one-end trick, the sequential propagator technique, and the covariant approximation averaging (CAA) can reduce computational costs and noise contamination.

Using the improved calculation scheme, we next investigate the rho resonance appearing in the  $I = 1$  two-pion interaction with large box size and small pion mass enough for the rho meson to be a resonance[3]. We succeed in determining the non-local potential at the next-to-next-to-leading order of the derivative expansion for the first time. The potential reproduces a typical resonance behavior of the scattering phase shift, and resonance parameters are extracted directly from the pole search of the S-matrix via the complex-scaled Schrödinger equation. We find that the resonance mass is consistent with the value in the literature, while the coupling turns out to be somewhat larger. The latter observation may be attributed to the truncation error of the derivative expansion in a near-threshold region, where the center-of-mass energy levels cannot cover.

We finally study the laboratory frame formalism of the HAL QCD method with the one-end trick. The laboratory frame calculation can be applied to reduce systematics appearing in the resonance study, for example, the truncation error of the derivative expansion and the vacuum contamination. We calculate the  $I = 2$  two-pion interaction from both the laboratory frame and center-of-mass frame formalisms and compare those results with each other. The potentials extracted from the laboratory frame NBS wave function gives consistent phase shifts with that of the center-of-mass frame as well as values obtained by Lüscher's method.

Our series of studies on the cooperation of the all-to-all propagators and the HAL QCD method establishes one of the promising ways to study hadronic resonances from lattice QCD. Furthermore, our calculation scheme can be applied to other interactions. We also mention future applications of our strategy to both exotic resonances and other interactions.

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# Four-dimensional effective action from non-Abelian DBI action with magnetic flux background

素粒子論研究室 阿部慶彦

**Abstract** We study a systematic derivation of four-dimensional  $\mathcal{N} = 1$  supersymmetric effective theory from ten-dimensional non-Abelian Dirac-Born-Infeld action compactified on a six-dimensional torus with magnetic fluxes on the D-branes. We derive a new type of matter Kähler metric and find that a gauge kinetic function and a superpotential are consistent with previous studies.

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Superstring theory is an attractive candidate for a unified theory consistent with quantum gravity. The string theory can predict the existence of extra dimensions and D-branes. Dynamics of low energy excitations on D-brane is described by gauge theories. The chiral matter fields are realized by introducing magnetic fluxes on the world volume of D-branes in the compact extra dimensions (The typical zero mode wavefunctions are shown in Fig. 1). The low energy effective theories have been discussed through compactification of higher-dimensional super Yang-Mills theory [1,2].

In this work, we study a systematic derivation of four-dimensional  $\mathcal{N} = 1$  supersymmetric effective theory from ten-dimensional non-Abelian Dirac-Born-Infeld action to include more stringy higher order corrections. We focus on the bosonic part up to  $\mathcal{O}(F^4)$  in compactifying this action on a six-dimensional torus with magnetic fluxes on the D-branes. We find a new type of matter Kähler metric while a gauge kinetic function and a superpotential are consistent with previous studies. This new matter Kähler metric is independent of the flavor but depends on the background fluxes, four-dimensional dilaton, Kähler moduli and complex structure moduli. We read the superpotential from an F-term scalar quartic coupling derived from the ten-dimensional action and the contribution of the new matter Kähler metric to the scalar potential turns out to be consistent with the  $\mathcal{N} = 1$  supergravity formulation. This talk is based on Ref. [3].

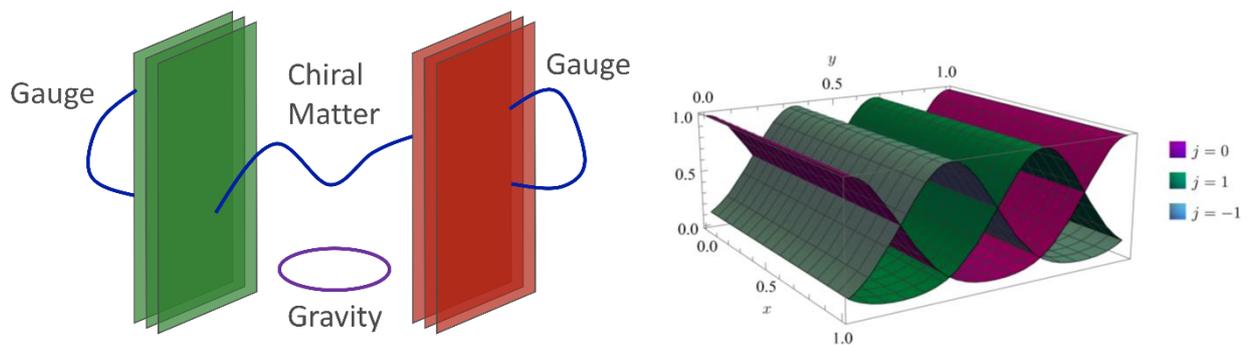


Figure 1: (Left) Magnetized D-branes and string spectra. (Right) Wavefunctions on a magnetized torus

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# Search for the $nn\Lambda$ state via the ${}^3\text{H}(e,e'\text{K}^+)\text{X}$ reaction at JLab

原子核ハドロン物理学研究室 鈴木一輝

**Abstract** We performed a search experiment for the  $nn\Lambda$  states using the  ${}^3\text{H}(e,e'\text{K}^+)\text{X}$  reaction at Jefferson Laboratory. In the experiment, no peak structure with a statistical significance exceeding  $3\sigma$  was observed. The upper limit of the  $nn\Lambda$  production cross section was obtained for the first time.

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In 2013, the existence of the  $nn\Lambda$  bound state with a binding energy of about 0.5 MeV was claimed by the HypHI collaboration at GSI [1]. Considering that the ground-state binding energy of hypertriton that is the isosinglet state ( $I = 0$ ) is as small as 130 keV, the  $nn\Lambda$  ( $I = 1$ ) state is hard to be bound. In contrast, several theoretical calculations suggest the existence of a resonant state near the threshold. Therefore, it is desirable to conduct  $nn\Lambda$  search experiments that can explore a wide range from the bound region to the resonance region. In the electro-production of hypernuclei, the  $nn\Lambda$  state can be investigated by using a tritium target ( $pnn$ ) by changing a proton to  $\Lambda$ . We performed a search experiment for the  $nn\Lambda$  states using the  ${}^3\text{H}(e,e'\text{K}^+)\text{X}$  reaction at the experimental Hall A in Jefferson Laboratory [2].

The experiment was performed using a 4.32-GeV electron beam. The momenta of the scattered electron and  $\text{K}^+$  were measured by the existing spectrometers, HRS-L and HRS-R, respectively. The central momenta of the scattered electron and  $\text{K}^+$  were set to cover the expected kinematics of  $nn\Lambda$  production, which were 2.22 and 1.82 GeV/ $c$ , respectively. To estimate the various efficiency and correction factors required for cross-section analysis, a Monte Carlo simulation was newly developed to reproduce the experimental data in the framework of Geant4.

There seemed some enhancement around the energy threshold of the  $nn\Lambda$  bound state in the cross-section spectrum for the  ${}^3\text{H}(\gamma^*,\text{K}^+)\text{X}$  reaction. However, no clear peak structures were observed. Therefore, spectral fits with assumed peak position  $B_\Lambda$  and decay width  $\Gamma$  were performed to quantitatively discuss the excess above the expected background distribution. Typical theoretical predictions that show the small and large decay widths were used for the fits, which are  $(-B_\Lambda, \Gamma) = (0.25, 0.8)$  MeV [3] and  $(0.55, 4.7)$  MeV [4]. As a result of the fitting, no peak structure with a statistical significance exceeding  $3\sigma$  was observed. The upper limit of the differential cross section at the 90% confidence level was obtained to be 21 and 31 nb/sr, respectively, when  $(-B_\Lambda, \Gamma) = (0.25, 0.8)$  and  $(0.55, 4.7)$  MeV were assumed. In addition, the cross-section upper limit with various  $B_\Lambda$  and  $\Gamma$  other than the above fixed assumptions were obtained to provide data that are independent on the theoretical predictions.

The upper limit of the  $nn\Lambda$  production cross section was obtained for the first time. In the theoretical calculations, the existence of the  $nn\Lambda$  resonant state strongly depend on the models of the  $\Lambda n$  interaction and calculation methods. The present result would constrain the interaction models and calculation methods. Theoretical calculations of the  $nn\Lambda$  production cross section to be compared with the present result are highly desirable.

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# 偏光 $\gamma$ 線源を用いた時間-偏光メスバウアースペクトル測定法の研究

核放射物理学研究室 田嶋 寛介

## Abstract

We developed a polarized  $\gamma$ -ray source and the polarization properties of the  $\gamma$ -rays were investigated. Furthermore, an advanced Mössbauer spectroscopic system that can measure time spectrum and polarized Mössbauer spectrum simultaneously was developed for advanced  $\gamma$ -ray optics studies.

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メスバウアー効果により放射性同位体から放出される無反跳  $\gamma$  線は物性研究の分野に利用されてきた[1]。近年では無反跳  $\gamma$  線を用いた電磁誘導透過現象や、コヒーレントな  $\gamma$  線波形制御といった  $\gamma$  線領域の基礎過程に着目した量子光学的な研究が盛んに行われている[2,3]。可視光と比較すると  $\gamma$  線は高空間分解能や光学的な厚みのある物体に対する高い透過性を有するといった特徴を持つ。とくにメスバウアー効果による無反跳過程由来の  $\gamma$  線では、その核種によってエネルギー分解能が  $\Delta E/E \sim 10^{13}$  にも達し、さらには偏光や時間領域の構造の制御に関する理論的なフレームワークの構築や実験の発展が進んでおり、従来の物性研究などへの応用にとどまらず、量子情報や量子通信といった分野への応用が期待されている[4]。本研究ではこれらの研究に関連して、磁場印加による偏光  $\gamma$  線源のメスバウアースペクトル制御実験と、時間-偏光メスバウアースペクトル測定の開発を行った。

メスバウアー分光に一般的に用いられるシングルラインの線源は偏光の情報を必要とする実験に適していない。我々は LINAC の電子線を Ni フォイルに照射することでピークが磁気的に分裂した  $^{57}\text{Co}$  の偏光メスバウアー線源を作成した。さらにこの線源に外部磁場を印加することで、 $\gamma$  線の放射方向および特定の偏光に対応するピークが制御されることを確認した (Fig.1)。

高度化される  $\gamma$  線量子光学研究では、 $\gamma$  線源やサンプルに時間変動する磁場のような様々なパラメータの摂動を有する測定が要求される。従来のハードウェアを用いたエネルギー弁別、時間弁別による測定系ではこのような要求に対応するのが難しい。そこで我々は高性能 multi-channel-scaler(MCS6, FAST ComTec)を使用し、検出した  $\gamma$  線それぞれの時刻と対応するトランスデューサの速度を記録する測定系を開発した(Fig.2)。この測定系では、一度の実験でメスバウアースペクトルと時間スペクトルを測定できるだけでなく、摂動に対応した時間領域のメスバウアースペクトルの測定といった自由度の高い測定も可能であり、当該領域研究のさらなる進展が期待される。

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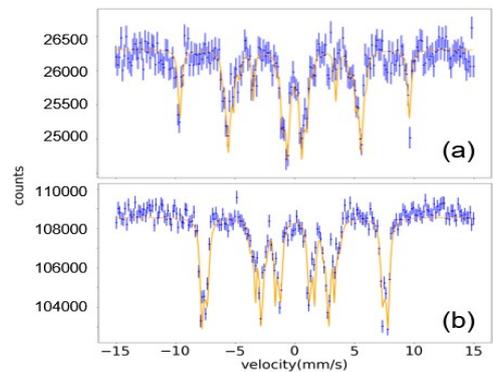


Fig. 1 Mössbauer spectra of a Fe foil using a  $^{57}\text{Co}$  in Ni source; external magnetic fields were applied to the Fe foil and the  $^{57}\text{Co}$  in Ni foil source.

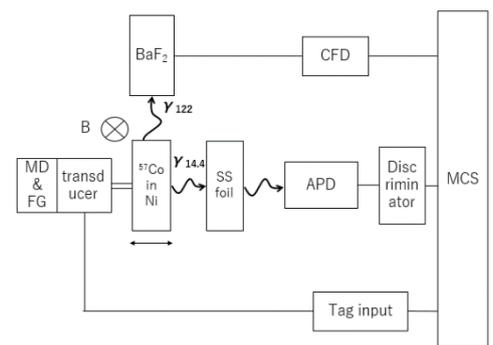


Fig. 2 Block diagram of the system for developed measurement system.

# 機械学習を用いた粒子識別技術の開発と $^{24}\text{Mg}$ における $6\alpha$ 状態の探索

原子核・ハドロン物理学研究室 藤川祐輝

**Abstract** Alpha condensation is one of the most important phenomena in the nuclear structure. We are going to search for the 6 alpha condensed state in  $^{24}\text{Mg}$  using the  $^{12}\text{C}+^{12}\text{C}$  resonance scattering. In order to carry out this experiment, we developed the PID method using machine learning technique.

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原子核の構造は、核子が平均ポテンシャル中で単一粒子軌道を占有するという殻模型でよく説明できる。一方で、殻模型で説明することが難しく、複数の核子が強い相関を持つクラスター模型によって説明される状態の存在が知られている。原子核において最も重要なクラスター相関は、陽子 2 個と中性子 2 個が粒子として相関する $\alpha$ クラスター相関である。実際に、 $^{12}\text{C}$ における $0_2^+$ 状態は空間的に発達したクラスター状態として最も広く知られた $\alpha$ クラスター状態であり、Hoyle 状態と呼ばれている。この $0_2^+$ 状態は、3 つの $\alpha$ クラスターが最低エネルギー軌道に凝縮した $\alpha$ 凝縮状態であり、密度が標準核子密度の 20%-25%という低密度状態になっていると指摘されている [1]。

このような $\alpha$ 凝縮状態は、 $^{12}\text{C}$ 以外の自己共役な $A = 4k$ 核においても普遍的にその存在が予言されており、 $k = 10$ の $^{40}\text{Ca}$ まで準安定的に存在すると予想されている [2]。しかし、 $\alpha$ 凝縮状態の存在が確立しているのは $^8\text{Be}$ と $^{12}\text{C}$ の 2 核種のみであり、それより重い核種に関しては $^{16}\text{O}$ と $^{20}\text{Ne}$ について実験的に候補が示されているのみである [3-6]。そこで我々は、次に軽い $4k$ 核である $^{24}\text{Mg}$ における $\alpha$ 凝縮状態探索実験を計画している。

本研究では、ビームエネルギーを変えながら $^{12}\text{C} + ^{12}\text{C}$ 共鳴散乱を測定することで、 $^{24}\text{Mg}$ の励起エネルギーを走査し、励起状態からの複数の崩壊粒子を測定することにより $6\alpha$ 凝縮状態の同定を行う。 $\alpha$ 凝縮状態から放出される $\alpha$ 粒子は非常に低エネルギーであるため、粒子識別が困難である。さらに、 $6\alpha$ 凝縮状態からは最大 6 個の $\alpha$ 粒子が放出されるため、すべてを検出するためには大立体角を覆う必要がある。これらの要件を満たすために、機械学習を用いた波形解析による粒子識別技術の開発、および波形解析に特化した NTD Si を用いた大面積 Si 検出器「SAKRA」の開発を行った (Fig. 1)。

本発表では主に、日本原子力研究開発機構タンデム加速器施設で行った、粒子識別技術開発のためのテスト実験、および $^{12}\text{C} + ^{12}\text{C}$ 散乱の予備測定の結果について述べる。粒子識別に関しては、2 MeV以上の粒子に対して全チャンネルで 90%以上の識別性能が得られ、散乱実験を行うのに十分な性能が確認された。今後は、機械学習アルゴリズムの改善を行い、さらなる性能向上を目指す。また、 $^{12}\text{C} + ^{12}\text{C}$ 散乱の測定では、 $6\alpha$ 凝縮状態の同定に重要な $3\alpha + ^{12}\text{C}$ イベントを確認した。予備測定において、本測定手法の妥当性を確認できたため、2022 年 4 月に、SAKRA 検出器を用いて $6\alpha$ 凝縮状態を探索する 6 日間のビームタイムを予定している。

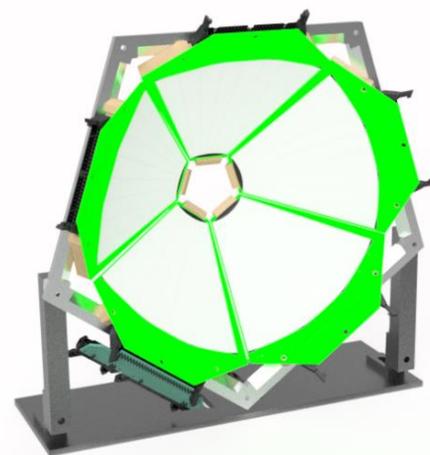


Fig. 1. Si detector array “SAKRA”.

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# 2種類のスpekトラムの精密測定から迫る ニュートリノにおける CP 対称性の破れの探索

高エネルギー物理学研究室 安留健嗣

**Abstract** Neutrino oscillation measurements exploring CP violation in the lepton sector are probes to solve the mystery of the universe's matter-antimatter asymmetry. This research presents an analysis of neutrino-nucleus interactions at two different neutrino energies in order to increase the sensitivity of searches for neutrino CP violation at the T2K experiment.

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素粒子物理学の課題の一つに、物質優勢宇宙の謎がある。現在の宇宙は物質に満ちているが、宇宙創生時には物質・反物質がほとんど等しく存在していたと考えられている。どのような過程を辿り、反物質が消滅し物質だけが生き残ったかは解明されていない。粒子・反粒子対称性の破れ（CP 対称性の破れ）は、物質優勢宇宙の謎に迫る有力な切り口となると期待されている。クォークセクターにおいては CP 対称性の破れが確認されているが、破れの効果は小さくレプトンセクターにおけるその発見が切望されている。ニュートリノは、質量の異なる3種類の波の重ね合わせによって定義される素粒子である。飛行中にそれぞれの波の位相が変化することにより、異なるフレーバーのニュートリノが発現する（ニュートリノ振動）。ニュートリノと反ニュートリノの振動確率を精密に測定することにより、レプトンセクターにおける CP 対称性の破れを探索することが可能となる。

Tokai to Kamioka 実験（T2K）は茨城県東海村にある大強度陽子加速器施設（J-PARC）において（反）ミューオンニュートリノを生成し、295 km 離れたニュートリノ検出器スーパー・カミオカンデ（SK）に打ち出し、（反）電子ニュートリノに振動する確率を測定する。最新結果では、CP 対称性の破れを 90% の信頼度で示唆する結果を公表した[1]。信頼度の向上には統計誤差と系統誤差の削減が課題であり、支配的な系統誤差をもたらすニュートリノ反応モデルの理解が探索感度を改善する鍵となる。T2K におけるニュートリノのエネルギーは 1 GeV 程度であり、その領域におけるニュートリノ反応は原子核の多体効果の影響を受けるため、精密な測定が難しい。T2K 実験では前置検出器 ND280 の測定により、ニュートリノ反応モデルの理解を進めている。ニュートリノのエネルギースペクトラムは幅が広く、ニュートリノ振動確率はエネルギーに依存するため、1 GeV 付近の様々なエネルギーでのニュートリノ反応を理解することが重要となる。そこで、ND280 が測定するエネルギー領域とは異なる領域でニュートリノ反応断面積の精密測定を行い、T2K の系統誤差を削減する実験（ワガシ実験）を立ち上げた。ワガシ実験の標的検出器にも工夫がある。SK は H<sub>2</sub>O 標的であり全方向に等しく感度があるのに対し、ND280 の主標的は CH であり測定のアクセプタンスが前方に偏っている。ワガシ実験の標的検出器は H<sub>2</sub>O を主標的とし、大角度に散乱する粒子に対して前方に散乱する粒子と同等の検出効率を持つため、ND280 に比べ SK に対する標的やアクセプタンスの違いが小さく精密な測定が可能で、ニュートリノ反応の不定性を削減することが期待される。さらに、ND280 とワガシ実験による測定結果をニュートリノ振動解析に同時に適用することで、ニュートリノにおける CP 対称性の破れに対する感度の向上を目指している。

ワガシ実験は、2019 年に計 6 台の検出器のインストールを完了した。同年から物理測定を開始し、3 ヶ月分のビームデータを取得した。各検出器について、光量・検出効率・飛跡再構成効率・反応点・飛跡の角度・運動量・電荷の再構成精度を評価し、解析の枠組みを構築した。またニュートリノ振動解析の主な信号事象である、 $\pi$  中間子を伴わないニュートリノ荷電カレント反応事象に対する選択アルゴリズムを考案し、選択効率 20%、純度 70% の測定が可能であることを検証した。本発表では、ワガシ実験立ち上げから測定データを用いた検出器の性能評価の結果、シミュレーションを用いた事象選択における信号事象と背景事象の弁別について発表する。

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# Binary and Fireball as Possible Origins of Fast Radio Bursts

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**Abstract** As the origin of periodic fast radio bursts (FRBs), we consider a binary and restrict the parameter space of the source binary. We also consider a baryon-loaded fireball from a magnetar as the origin of FRB associated with the Galactic magnetar bursts.

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Fast radio bursts (FRBs) are one of the main targets of astrophysics today. FRBs are bright radio transients, and their duration is of the order of milliseconds. From observed properties, most FRBs have been shown to have extragalactic origins. The brightness temperature is  $T \sim 10^{36}$  K, which is extremely high and suggests coherent emission. Some FRBs show bursts repeatedly, and they are called repeaters. Although so many bursts have been observed, their source and emission mechanism are not understood (e.g., [1]).

Among many FRBs, some unique FRBs have been identified. Two FRBs, FRB 20180916B and FRB 20121102A, show periodic activity. For a period of the order of ten to a hundred days, FRBs are only detected in an active window of the order of a few tens percent. The origin of this period is not well understood. We first consider a binary as the origin of this periodicity. We develop "binary comb model", which was applied to FRB 20180916B by Ioka & Zhang [2], and apply the developed model to interpret FRB 20121102A [3]. We introduce an eccentricity into the orbit and identify two new modes of the binary comb model. Our developed model expands the applicable parameter space, allowing the companion star to be a massive star, a massive black hole, or a supermassive black hole. For FRB 20121102A, we show that a black hole binary or supermassive black hole binary has larger parameter spaces. These models are also consistent with other observations, such as the persistent bright radio counterpart associated with the source.

Another unique FRB is the Galactic FRB, FRB 20200428A, which is associated with an X-ray burst from a magnetar, SGR 1935+2154 (e.g., [4]). The luminosity of X-ray burst is about the same as other bursts from SGR 1935+2154, but the peak energy is higher than that of typical bursts. As FRB 20200428A shows, magnetar bursts would be closely related to the origin of FRBs. We consider the dynamics of the fireball in the magnetar burst. Specifically, we consider a baryon-loaded fireball expanding along open magnetic field lines. An expanding fireball is likely to be involved as a mechanism for producing thermal radiation with observed high peak energy. The baryon loading on this fireball naturally occurs, but the dynamics of this fireball have not been investigated. We create a unified picture of this fireball, taking into account the photon escape via two processes (optical thinning and diffusion), the number density in a strong magnetic field, and the cross section in a strong magnetic field. Five cases of photon escape are identified. We show that the baryons loading increases the final Lorentz factor, and the kinetic luminosity of the outflow can be higher than the observed FRB luminosity for the observed X-ray photospheric luminosity. We also analytically evaluate the baryon loading parameter where the electrons associated with the baryons in the magnetar burst can affect the propagation.

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# Algebraic tensor models: a potential spacetime interpretation of the canonical tensor model

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**Abstract** In the context of quantum gravity, we develop and investigate a new mathematical framework to describe gravitational degrees of freedom in a tensorial quantity. Such quantities are used in the canonical tensor model, and we aim to construct a rigid spacetime interpretation using this approach.

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The quantisation of gravity is one of the central fundamental open questions in theoretical physics. The usual approach is to describe the gravity degrees of freedom in terms of the metric tensor field (or related variables) and attempting to quantise this. Several discrete approaches exist, notably the canonical tensor model [1], which uses a symmetric tensor as its fundamental configuration space variable and manages to straightforwardly quantise this. The ability to easily quantise the model, as opposed to other models, makes it very attractive. However, though a tensor is then supposed to describe a spatial slice of spacetime, the direct correspondence between the tensor and topological spaces is not directly clear despite results suggesting the recovery of topological and geometric data using methods from data analysis [2].

In this study, I will present an approach to describe the gravitational degrees of freedom in terms of a real symmetric tensor by taking serious the duality between associative commutative algebras and topological spaces [3]. The benefit of this approach is that the geometric degrees of freedom of a compact Riemannian manifold may be captured in a countably infinite-dimensional tensorial object, as opposed to the overcountably infinite-dimensional configuration space of the metric tensor, and opens the door to a possibility to describe a certain class of fuzzy spaces by taking finite dimensional tensors into account. This method may provide a sound interpretation of the canonical tensor model as a model for quantum gravity, and some previous results regarding this model will be examined.

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