様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

令和　６ 年　６ 月　６ 日現在

機関番号：１２６０１
研究種目：基盤研究(B)（一般）
研究期間：2020～2023
課題番号：２０Ｈ０１８９６

研究課題名（和文）Effective field theory for sub-MeV dark matter direct detection

研究課題名（英文）Effective field theory for sub-MeV dark matter direct detection

研究代表者
Ｍｅｌｉａ　Ｔｈｏｍａｓ（Melia, Thomas）

東京大学・カブリ数物連携宇宙研究機構・准教授

研究者番号：３０８１４９０９

交付決定額（研究期間全体）：（直接経費）　　12,630,000円

研究成果の概要（和文）：この研究により、有効場の理論の理解がさらに深まり、より広範囲の物理システムに適用できるように、既知の構築技術を開発および一般化しました。主な成果は、暗黒物質が凝縮系の原子間距離よりも大きいドブロイ波長を持つ場合の暗黒物質の直接検出に関連する有効場の理論について、より広範な理解を深めたことでした。このような凝縮物質系内のフォノンを記述する新しい有効場の理論が書き留められました。いわゆる外部自己同型対称性の新しい理解が明らかになりました。対称性を破るが、有効場の理論に南部ゴールドストーン粒子が存在しない新しい方法が解明されました。

研究成果の学術的意義や社会的意義
Dark matter is one of the greatest puzzles in physics, and is a mystery that has gone unsolved for decades. Understanding the nature of dark matter has a direct impact on our very own existence in the universe, since without the effect of dark matter on the cosmos, we would not be here.

研究成果の概要（英文）：This research furthered our understanding of effective field theory, developing and generalising previously known techniques for their construction so as to be applicable to a much wider range of physical systems. A key achievement was to develop a broader understanding of the effective field theories relevant for dark matter direct detection in the case that the dark matter has a de Broglie wavelength greater than the interatomic spacing of condensed matter systems. New effective field theories that describe the phonons within such condensed matter systems were written down. A new understanding of so-called outer-automorphism symmetries was uncovered. A new way of breaking a symmetry but not having any Nambu-Goldstone bosons in the effective field theory was elucidated.

研究分野：Theoretical particle physics

キーワード：Dark matter　Effective field theory

※科研費による研究は、研究者の自覚と責任において実施するものです。そのため、研究の実施や研究成果の公表等については、国の要請等に基づくものではなく、その研究成果に関する見解や責任は、研究者個人に帰属します。

１．研究開始当初の背景

The evidence for dark matter in the universe is overwhelming, ranging from the detailed measurements of the cosmic microwave background to observations of colliding galaxy clusters and rotation curves of stars in galaxies. We know that dark matter contributes to the energy budget of the universe, but as we only see the gravitational interactions of dark matter, we do not have any indication of its mass scale. Past theoretical and experimental efforts have been focused on a very narrow window of masses that are associated with the so-called weakly interacting massive particle. However, null results from underground experiments and the large hadron collider at CERN have thrown this paradigm into question. And so new theoretical and experimental effort is being put into understanding other regions of possible dark matter mass.

One such region is to consider particles that are less massive than the typical weakly interacting massive particle, with mass below a MeV. For such dark matter, there exist theoretical models which can explain the relic abundance (amount) of dark matter in the present-day universe, and so their study is motivated. It is possible that such dark matter in the milky way could be detected through a non-gravitational interaction in a laboratory experiment. These experimental efforts typically utilise on research and development ideas in new quantum technologies, because the amount of energy deposit is very small (around a million times smaller than the mass-energy of the dark matter).

However, a crucial point is that at such small masses, the de Broglie wavelength of the dark matter becomes larger than the typical interatomic spacing in condensed matter systems. Thus the dark matter does not scatter of individual atoms of the detector material, but rather interacts with collective modes of the detector (e.g. phonons), So the relevant theory needs to take this into account.

Effective field theories are ‘catch-all’ quantum theories that can quantitatively parameterise unknown physics, and can also been seen as a systematic organisation of the intuition we obtain from the so called renormalization (coarse-graining procedure) of quantum field theory. In principle, an effective field theory can be written down knowing two things: the known degrees of freedom at the relevant energy scale, and the symmetries of the system.

My prior work dealt with systematically understanding the effective field theory construction in the case that there was Poincare symmetry (relativistic symmetry). However, the motivation for this project was to be able to systematically write down effective field theories for condensed matter systems that act as dark matter detectors, and that can describe the dark matter - detector interaction. These non-relativistic condensed matter systems fall outside of the symmetries considered in the prior work,

The key motivation for this effective field theory approach to describe dark matter - detector interactions is that broad lessons could be learned about how dark matter interacts with proposed materials for such detectors. For example, it is crucial to understand how scattering rates may be increased, as this will lead to a greater chance of discovery of non-gravitational dark matter interactions. And indeed, prior background work showed that naive expectations (from e.g. dimensional analysis) of dark matter - detector cross sections were wrong.

Another motivation was that in generalising the systematic study of effective field theories to systems that are non-relativistic, more foundational aspects of their mathematical structure could be elucidated. Already in relativistic systems connections were made to conformal representation theory, commutative algebra and cohomology, as well as the spinor helicity formalisms from scattering amplitudes. Because the structure of non-relativistic theory is much richer, it was expected that deeper mathematical lessons could be extracted.

２．研究の目的

The objective of this research was to develop the method of systematically constructing effective field theories that are relevant for the field of light dark matter detection. The plan was to build upon prior work of mine that uncovered systematic frameworks for the construction of effective field theories, and develop these frameworks to be of use for dark matter physics where the mass of the dark matter particle is below an MeV.

３．研究の方法

A key tool for the systematic construction of relativistic effective field theories was a mathematical object called a Hilbert series. These enabled a systematic enumeration of the various types of physical couplings that can be present in the effective interactions of the various relevant degrees of freedom of the system, subject to symmetry constraints. Developing the Hilbert series technology was a key method in the research plan.

The Hilbert series technique had previously been identified with the construction of a partition function of the free theory of the relevant degrees of freedom. Partitions are complicated objects to study, and the precise combinatorial calculations becomes very cumbersome and computationally expensive. One well-known analytic handle is to study their asymptotic behaviour (as in the famous Ramanujan formula for partitions of integers), and this approach could be generalised to apply to Hilbert series as well.

Another important method was to actually construct and study scattering in effective field theories that are relevant for condensed matter systems, with particular attention being paid to the mathematical structures that are relevant for doing so. In particular the spinor helicity method and related geometric understanding was to be further elucidated.

４．研究成果

One of the first key main results of this project was to write down a novel effective field theory for phonons in a material that consists of two distinct types of atoms. Attention was paid to the symmetry breaking pattern that in turn dictates the interactions of the theory. The symmetry breaking was describing how the Poincare symmetry (and an internal symmetry) was broken, so as to give rise to Nambu Goldstone bosons which are identified as the phonons of the theory. It was shown that such symmetry arguments lead to some of the phonons getting a small 'gap' (in that their energy does not go to zero as their momentum goes to zero). We dubbed such phonons pseudo-acoustic phonons, and pointed out that one such material that they are of relevance to is bi-layer graphene. One of the results was to understand how phonons may get a 'gap' purely on symmetry (i.e. effective field theory) arguments, as this can change their detection probability and the rate at which dark matter scatters off them. This research was done with international collaboration, led to a publication in an international journal, and to talks at international conferences and seminars.

Another main result was how the spinor helicity variables motivated a geometerization of a number of scattering observables in quantum field theory, such as differential cross sections. This work was published in an international journal, and was done with international collaboration.

The asymptotic handle on Hilbert series was developed over two papers published in international journals, with international and domestic collaboration, and was presented at a number of international workshops and seminars. It was shown that by developing a mathematical theorem of Meinardus (from the 1950s) it could be applied to Hilbert series relevant for effective quantum field theories including particles of various helicity, and with various internal quantum numbers.

The Ising model is the archetypal condensed matter field theory, as many microscopic theories of interest fall within this universality class. With international collaborators I developed techniques to renormalise the quantum effective field theory of a real and a complex scalar field, and compute the anomalous dimensions to state-of-the-art loop order. We proved novel 'non-renormalization' theorems that give important information on how the coupling constants of the effective field theory change upon coarse-graining. This elucidated new structure in effective field theory. The results were published in two papers in international journals.

One of the unexpected results came about in discovering that an important symmetry that determines how a dark matter particle may interact with normal matter (that are known as outer-automorphism symmetries) may in fact be 'anomalous' (not preserved in the quantum theory). Because the organisation of interactions by these outer-automorphism symmetries is important, it was necessary to understand this surprising fact. This resulted in domestic and international collaboration, and resulted in a paper that was published in an international journal, and presented at an international conference.

Another key development of the Hilbert series technology was elucidating how it can be used to construct effective field theories where a gauge symmetry is spontaneously broken. This had actually not been understood in the relativistic setting, and this was achieved during the course of this research. It was shown that Hilbert series can also be applied to this important class of effective field theories. This was done within a domestic and international collaboration, and resulted in a paper that was published in an international journal, and presented at an international conference.

A novel and unexpected result, which has led to new research directions, is a new mechanism that describes the ability to 'evade' the theorem that Nambu Goldstone bosons are present when a symmetry is spontaneously broken. Famously, one such mechanism is the Higgs mechanism, where a vector boson acquires a mass. In this case, the degree of freedom associated with the Nambu Goldstone boson shows up in the longitudinal degree of freedom of the massive boson. In an international collaboration we showed how free choices of the electric and gravitational fields in the quantum theories of electromagnetism and gravity is equivalent to the existence of a charged or gravitational fluid in these theories respectively. This fluid breaks Lorentz symmetry, but does not have an associated Nambu Goldstone boson degree of freedom. This is possible down to the gauge nature of these theories. This work is currently submitted to a journal, and has been presented in international conferences and talks.

5．主な発表論文等

〔雑誌論文〕　計12件（うち査読付論文　11件／うち国際共著　12件／うちオープンアクセス　12件）

1．著者名 Kondo Dan、McGehee Robert、Melia Tom、Murayama Hitoshi	4．巻 2022
2．論文標題 Linear sigma dark matter	5．発行年 2022年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP09(2022)041	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Graf Lukas、Henning Brian、Lu Xiaochuan、Melia Tom、Murayama Hitoshi	4．巻 2023
2．論文標題 Hilbert series, the Higgs mechanism, and HEFT	5．発行年 2023年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP02(2023)064	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Cao Weiguang、Herzog Franz、Melia Tom、Roosmale Nepveu	4．巻 -
2．論文標題 Non-linear non-renormalization theorems	5．発行年 2023年
3．雑誌名 arxiv 2303.07391	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Burns Anne-Katerine、Kaplan David E、Melia Tom、Rajendran Surjeet	4．巻 -
2．論文標題 Time evolution in quantum cosmology	5．発行年 2022年
3．雑誌名 arxiv 2204.03043	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Cao Weiguang、Herzog Franz、Melia Tom、Nepveu Jasper Roosmale	4．巻 2021
2．論文標題 Renormalization and non-renormalization of scalar EFTs at higher orders	5．発行年 2021年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP09(2021)014	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Larkoski Andrew J.、Melia Tom	4．巻 2021
2．論文標題 A large-N expansion for minimum bias	5．発行年 2021年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP10(2021)094	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Henning Brian、Lu Xiaochuan、Melia Tom、Murayama Hitoshi	4．巻 2022
2．論文標題 Outer automorphism anomalies	5．発行年 2022年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP02(2022)094	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Cao Weiguang、Melia Tom、Pal Sridip	4．巻 -
2．論文標題 Universal fine grained asymptotics of weakly coupled Quantum Field Theory	5．発行年 2021年
3．雑誌名 arxiv 2111.04725	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Esposito Angelo、Geoffray Emma、Melia Tom	4．巻 102
2．論文標題 Effective field theory for acoustic and pseudoacoustic phonons in solids	5．発行年 2020年
3．雑誌名 Physical Review D	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.102.105009	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Larkoski Andrew J.、Melia Tom	4．巻 102
2．論文標題 Covariantizing phase space	5．発行年 2020年
3．雑誌名 Physical Review D	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.102.094014	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Melia Tom、Pal Sridip	4．巻 10
2．論文標題 EFT asymptotics: the growth of operator degeneracy	5．発行年 2021年
3．雑誌名 SciPost Physics	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.21468/SciPostPhys.10.5.104	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Graf Lukas、Henning Brian、Lu Xiaochuan、Melia Tom、Murayama Hitoshi	4．巻 2021
2．論文標題 2, 12, 117, 1959, 45171, 1170086, …: a Hilbert series for the QCD chiral Lagrangian	5．発行年 2021年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP01(2021)142	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計8件（うち招待講演　8件／うち国際学会　7件）

1．発表者名 Tom Melia
2．発表標題 Outer automorphism anomalies
3．学会等名 DISCRETE 2022（招待講演）（国際学会）
4．発表年 2022年

1．発表者名 Tom Melia
2．発表標題 A large N expansion for minimum bias
3．学会等名 2nd AEI workshop（招待講演）（国際学会）
4．発表年 2022年

1．発表者名 Tom Melia
2．発表標題 Light dark matter detection: theory and chemistry
3．学会等名 Dark Side of the Universe conference（招待講演）（国際学会）
4．発表年 2022年

1．発表者名 Tom Melia
2．発表標題 Dark matter hunting at the intersection of particle physics, solid state and chemistry
3．学会等名 ISCO 2023（招待講演）（国際学会）
4．発表年 2023年

１．発表者名
Tom Melia

２．発表標題
Developments in Hilbert series for EFT

３．学会等名
HEFT 2021（招待講演）（国際学会）

４．発表年
2021年

１．発表者名
Tom Melia

２．発表標題
Detecting sub-MeV dark matter with chemistry and collective modes

３．学会等名
地下素核研究会（オンライン）（招待講演）

４．発表年
2021年

１．発表者名
Tom Melia

２．発表標題
A large-N expansion for minimum bias

３．学会等名
PANIC 2021（招待講演）（国際学会）

４．発表年
2021年

１．発表者名
Tom Melia

２．発表標題
New analytic probes of effective field theory

３．学会等名
NCTS Annual meeting, Taiwan（招待講演）（国際学会）

４．発表年
2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
英国	Edinburgh U			
スイス	U Geneva	EPFL		
米国	UC Berkeley	Johns Hopkins U	UC San Diego	他2機関
ドイツ	Humboldt U Berlin	Max Plank Institute Heidelberg	U.Heidelberg	
英国	Edinburgh U			