Introduction

Hello everyone.

Today I'd like to talk about axion electrodynamics.

You might be surprised that there is a picture of a laundry detergent here.

Don't worry, that will become clear later.

Overview

More preciously, I will explain what exactly an axion is and where it comes from.

To understand this, we need to talk about the strong CP problem, as well as the Peccei-Quinn mechanism which, in turn, postulates the Axion field.

Then I will introduce the topic of Axion electrodynamics in general, by looking at the work of Pierre Sikivie in this regard.

Furthermore we will explore the role of axions in cosmological scenarios.

And for the last part of the presentation, we will look at experiments that he proposed and which are currently under development or already returning data.

What is an axion

According to Wikipedia:

> The axion is a hypothetical elementary particle postulated by the Peccei–Quinn theory to resolve the strong CP problem in quantum chromodynamics (QCD).

I will describe the strong CP problem and the Peccei-Quinn theory in future slides.

Why are Axions interesting?

> If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter.

CP symmetry

> CP-symmetry states that the laws of physics should be the same if a particle were interchanged with its antiparticle (C symmetry, as charges of antiparticles are the negative of the corresponding particle), and then left and right were swapped (P symmetry).

Strong CP problem

This is the Lagrangian density of quantumchromodynamics, QCD in short.

Quantumchromodynamics is the quantum field theory of the strong interaction concerned with quarks, gluons and their color charge.

As shown by Gerard 't Hooft, pictured on the right, the Lagrangian density includes a potentially CP symmetry violating term due to its non-trivial vacuum structure.

Combined with effects generated by weak interactions, this effective periodic term, Theta, appears as a Standard Model input, which means that its value is not predicted by the theory and must thus be measured.

Strong CP problem

Neutron electric dipole moment

However, a large value for Theta and therefore large CP-violating interactions originating from QCD would induce a large electric dipole moment for the neutron.

So far, no electric dipole moment has been measured and experimental constraints on it imply that it if it still exists it has to be very very small. This in turn means that the CP violation from quantum chromodynamics must be extremely tiny as well and thus Theta must itself be extremely small.

The current limit on the neutronic electric dipole moment constrains this angle to be less than ten to the power of minus ten radians.

Since Theta could have any value between zero and two Pi, this presents a “naturalness” problem for the standard model.

In physics, naturalness is the property that the dimensionless ratios between free parameters or physical constants appearing in a physical theory should take values "of order 1" and that free parameters are not fine-tuned. That is, a natural theory would have parameter ratios with values around one and not around ten to the power of minus ten, as is the case with Theta here. Why should this parameter find itself so close to zero? Or asked differently, why should quantum chromodynamics find itself CP-preserving?

This question constitutes what is known as the strong CP problem.

Strong CP problem

Massless quarks

One simple solution exists: If at least one of the quarks of the standard model is massless, CP symmetry violation becomes unobservable.

However, empirical evidence strongly suggests that none of the quarks are massless.

Consequently, particle theorists sought other resolutions to the problem of inexplicably conserved CP.

Peccei–Quinn mechanism

Postulated by Helen Quinn and Roberto Peccei the therefore called Peccei–Quinn theory predicts that the small value of the Theta parameter is explained by a dynamic field, rather than a constant value.

The potential which this field carries causes it to have a value that naturally cancels, making the parameter Theta uneventfully zero.

On the left you can see them showing their theory with a sombrero modeling the graph of Goldstone's "Mexican Hat" potential, which is an example of a spontaneously broken symmetry, as you already heard in previous talks I think.

The axion field

Peccei–Quinn theory presents Theta as a functional component by introducing an addional symmetry. The Peccei-Quinn symmetry is spontaneously broken by the vacuum expectation value of Theta.

According to the Goldstone theorem a discrete, spontaneously broken symmetry corresponds to a new particle.

The Boson for the Peccei-Quinn symmetry was independently proposed by Frank Wilczek and Steven Weinberg, which are pictured on the right here.

Frank Wilczek named it after the laundry detergent called Axion, because it cleaned up a profound physical problem. Hence the picture in the title slide.

The axion field

Here f sub a is the scale of the breaking of the Peccei-Quinn symmetry, while a of x is the Nambu Goldstone axion field associated with the broken symmetry. The potential of the axion field drives it naturally to zero.

It is interesting to note that f sub a is inversely proportional to the mass and the coupling constant of the axion.

Possible axion models

The original Wilczek/Weinberg axion has since been ruled out but more recent axion models still hold up.

The properties of the axion depend mainly on the magnitude f sub a of the vacuum expectation value that spontaneously breaks the Peccei-Quinn symmetry.

As previously said the axion mass and its couplings to ordinary particles are all inversely proportional to f sub a.

As far as the solution to the strong CP problem is concerned, the value of f sub a is arbitrary.

Values for f sub a with less than ten to the power of eight Giga electron volt have since been ruled out by experiments and theoretical considerations. Possible axions need to have a vaccum expectation value even highter then that. These axions are so weakly coupled that they have been called "invisible". They are also absurdly light. If you had as many axions as there are grains of sand on Earth, their combined mass might equal that of a millionth of a billionth of a single sand grain.

Axion

If the "invisible axion" exists it has the following properties:

No electric charge and no spin.

A mass between one hundred-thousandth and one thousandth electron volt.

It interacts only gravitationally and electromagnetically but the electromagnetical interaction is very weak.

Due to its mass and weak electromagnetic interaction it is a good candidate for dark matter.

Axion electrodynamics

Pierre Sikivie published a modification of Maxwell's equations that arise from a light, stable axion in 1983, making the invisible axions visible.

In his paper he showed that the axions should be observable by multiple experimental setups.

All of which rely on the fact that the axion could transform into a photon (and viceversa) in the presence of electromagnetic fields. This property of the axion is crucial for most of the experimental strategies of axion detection.

Axion electrodynamics

Modified Maxwell's equations

As you can see the Maxwell's equations look very similar to the unmodified ones.

The expressions for the E- and B- fields are replaced by an expression including the axion field Theta coupled with a coupling constant Kappa.

Axion electrodynamics

Rotating E and B into one another

Incorporating the axion has the effect of rotating the electric and magnetic fields into each other, where the mixing angle Xi depends on the coupling constant Kappa and the axion field strength Theta.

In addition we also get a new differential equation - the axion law - which is simply the Klein–Gordon equation with an E and B source term.

The Klein-Gordon equation is the quantum field theory equation for massive spin-zero particles, as the axion is massless and spin zero as well.

Axion electrodynamics

With the modified equations Sikivie showed that the photons can be converted into axions and vice-versa in the presence of a magnetic field.

This is the basis for all the proposed experiments in his paper.

Here is how that process looks like in a Feynman diagram.

A is the axion and Gamma the converted photon. The doubled lines at the bottom together with the second wavy line indicate the magnetic field pushing the conversion.

Cosmological considerations

Axions may have played a critical cosmological role with regard to the problem of galaxy formation.

First, the primordial density perturbations from which galaxies evolved may have been produced by the presence of axionic domain walls for a limited time period in the early universe. Domain walls are topologically protected sheet-like surfaces that form when the potential of a field has a discrete symmetry that is spontaneously broken as is the case in the Peccei-Quinn mechanism.

Secondly, axions may be the stuff the dark halos of galaxies are made of. Because of their very large primordial phase-space density, axions cluster easily and if they have been produced abundant enough, they could even provide all of the halo matter.

They might be produced by the Primakoff effect. The effect, named after the physicist Henry Primakoff, describes the production of two pseudoscalar mesons by the interaction of high energy photons with an atomic nucleus.

Lastly, due to the aforementioned effect they should also be continually produced inside the sun.

Experiments

Sikivie proposed essentially two types of possible experiments:

If the axion exist and it is the main component of dark matter, the very relic axions that would be bombarding us continuously could be detected using microwave cavities, immersed in powerful magnetic fields, that are resonant to the axion mass.

Another promising detection technique, this one independent of the axion being the dark matter, is that of the axion helioscope, aiming to detect axions produced at the solar interior. These could be detected, once again, using a powerful magnet, but this time equipped with low background x-ray detectors.

Experiments

The axion haloscope

Using calculated estimates for the axion flux on earth based on the cosmological considerations described previously, Sikivie showed that it would be possible to build a detector combining a microwave cavity with a magnetic field to detect axions from the dark matter halo around our local galaxy, the Milky Way.

To do this the microwave cavity has to be resonantly tuned to frequencies corresponding to the assumed mass of the axion.

He proposed a dynamically extendable cavity in the detector, so that one can probe for different photon frequencies and therefore for different values of the axion mass.

In addition, because the interaction is so weak, it is necessary to reduce the background noise in the detector.

Also the magnetic field has to be inhomogeneous, because three-momentum must be provided for the transition to occur.

To achieve inhomogeneity of the magnetic field, Sikive proposed embedding wires of a superconducting metal in a material transparent to microwave radiation. When the detector is cooled below the critical temperature, the magnetic flux lines will be expelled from the superconducting wires and hence will be made inhomogeneous. Cooling the detector down has the added benefit of reducing noise, which as said is important as well.

Experiments

The axion helioscope

The idea here is the same as the previous one but now applied to the solar axion flux.

Solar axions are expected to be produced by the Primakoff effect in the sun.

In a strong magnetic field, solar axions convert to x rays so we need an x ray detector instead of a microwave detector.

Current experiments

The Axion Dark Matter Experiment (ADMX in short) is an example of an haloscope originally proposed by Pierre Sikivie that searches for axions originating from the Milky Way galaxy. It includes many more technical advances and a lot of additional engineering work than in the original paper reducing the noise even further and making the experiment better suited to scan for a large range of possible axion masses. Sited at the Center for Experimental Nuclear Physics and Astrophysics at the University of Washington, ADMX is a large collaborative effort with researchers from universities and laboratories around the world.

Another experiment that builds on Sikivie's work is the Axion Solar Telescope at CERN (CAST in short) in Switzerland is an example of an axion helioscope that searches for axions produced inside of the sun.

As a successor to CAST, The International Axion Observatory (IAXO in short) is a proposed fourth generation axion helioscope. It aims at a much improved sensitivity with respect to past and current axion searches, pushing the limits of possible axions even further.

In addition there are also a lot of other experiments that build on more subtler effects of axion electrodynamics that I will not mention in this talk. For instance there is the PVLAS experiment in italy. The name is an italian abbreviation that stands for "polarization of the vacuum with laser", as they explore the phenomena of vacuum magnetic birefringence.

Here you can see the ADMX set up, the actual detector is underground below the floor surrounded by the magnetic field. ADMX's central cavity automatically shifts its resonance frequency every hundred seconds and listens for axions' faint blip. The instrument hums along twentyfour-seven for nine months at a time. At this rate, it will take ADMX about five years to scan the full range it's designed to probe. It is the first machine to directly probe the axion's best-guess masses and to do so it is insanely sensitive. Placed on another planet, ADMX would be so sensitive that it could pick up cellular service from Earth. ADMX's lead scientist Leslie Rosenberg was quoted saying "We could easily get four bars on Mars with your cell phone — easy, no problem." Crazy right?

Summary

I would like to summarize my talk with the following key points.

The axion is an hypothetical particle that appears in extensions of the Standard Model of Particle Physics that include the so-called Peccei-Quinn mechanism. This mechanism was postulated already 35 years ago to explain an standing problem of the Standard Model: the strong-CP problem. The Peccei-Quinn mechanism was proposed to solve this problem in a natural way, without required parameter fine-tunning. As a collateral effect, however, a new particle appears, the axion, which may have important observable consequences.

In the first place, the axion is a neutral and very light (but not massless) particle, and it does not interact (or does it very weakly) with conventional matter. In some way one can see the axion as a “strange photon”.

In fact, theory predicts that the axion, if it exists, could transform into a photon (and viceversa) in the presence of electromagnetic fields. This property of the axion is crucial for most of the experimental strategies of axion detection.

One of the most suggestive properties of axions is that, in a natural way, they could be produced in huge numbers soon after the Big Bang. This population of axions would still be present today and could compose the Dark Matter of the Universe. The existence of Dark Matter is widely accepted in the scientific community, but its nature is still a mystery. Together with WIMPs, the axions are among the most searched candidates in the context of the nature of Dark Matter.

Further readings

Thank you for your time.

I hope I have managed to give a brief and not to technical overview of the strong CP problem, the axion field as its resolution and various methods to test the axion hypothesis.

The actual mathematics involved is quite complex so if you are interested to dig deeper I have some further readings for you:

First an introductory paper by Roberto Peccei himself that helped me understand the topic at hand.

A second paper autored by him might give an even broader overview including a chapter about the current axion models under review.

Also the official paper by Pierre Sikivie describing his insights into axion electrodynamcis. Since I didn't manage to get access to the paper via the UZH I used sci-hub. Accessing papers through sci-hub is legal in Switzerland and I highly advocate it since I don't believe in paid journals but an open access policy on scientific research.

Additionally I considered a lecture summary by N. Beisert, concerning mathematical symmetries in physics, which is quite comprehensive, to get a better understanding of symmetries in general.

And lastly, I can recommend this paper Tsou Sheung Tsun about symmetries in particle physics in special.