Nuclear and Particle Physics

Ravi Sharma
Washington Academy of Sciences

Abstract

We present a review of modern particle physics, current nuclear theories, and studies of dark matter. Physics is advancing rapidly as a result of new technologies that are being applied to the many unsolved problems. We hope to give some idea of the excitement in the field of modern physics today. This review is the first in a series of articles on physics.

Introduction

THE NATURE OF MATTER has long been the subject of philosophy and science. The Jains in India during the 6^{th} century BCE were the earliest to advocate that matter is composed of tiny uncountable and invisible particles called *permanu*. Later philosophers and scientists such as Democritus (c. 460–370 BCE) proposed similar theories in which the particles were indivisible elementary units. While it was well known, the atomic theory that matter is discrete rather than continuous was not generally accepted until 1908 when it was experimentally verified by Jean Perrin, who received the Nobel Prize in 1926 for his work.

The word “atom” comes from the Greek word $\alpha\tau o\mu\acute{\eta}$ meaning “uncuttable”. However, J.J. Thompson had already shown in 1897 that an atom has an internal structure, with his discovery of the electron. A decade later, Rutherford and his colleagues showed that an atom consists of electrons and a nucleus and that the nucleus is far smaller than the atom that contains it. Even when the atomic theory was finally verified experimentally, it was already known that an atom is not uncuttable, consisting of components that can be separated and rearranged. In 1936 it was experimentally shown that not only an atom but also its nucleus can be split apart (Lise Meitner and Otto Hahn) and that two nuclei can be fused (Hans Bethe). The constituents of nuclei, protons and neutrons, were themselves subsequently found to have still more elementary components. During all of this time, the notion of the most elementary constituents of matter continually changed as the technology for probing matter has improved.

Modern physics is a vast field of study that is rapidly advancing as new theories, techniques and experiments are being developed and new discoveries are being made. This article attempts to convey some of the excitement of physicists today. We begin with an overview of modern elementary particle physics in Section 2 and nuclear physics in Section 3. We then discuss one of the currently unsolved problems of modern physics, dark matter, in Section 4.

Modern physics has a very large number of specialized terms. The article ends with a glossary to help explain the terminology we will be using.

Elementary Particle Physics

The mathematical framework that is used for understanding elementary particles is Quantum Field Theory (QFT). This framework has also been applied in many other domains, although one usually uses the simpler Quantum Mechanics framework, which is the non-relativistic limit of QFT. Applications include condensed matter physics, chemistry, optics, integrated circuits, quantum computing, medical imaging, and many others. It has even been applied in everyday life situations with Quantum Decision Theory. A specific application of QFT is called a *model*, but it is not uncommon to use the word “theory” for what should properly be called a model.

In elementary particle physics there are four types of force; namely, electromagnetic, weak, strong (nuclear) and gravitational forces. The QFT model of electromagnetism is quantum electrodynamics (QED); the QFT model of the weak force is quantum flavourdynamics (QFD); and the combination of QED and QFD is electroweak theory (EWT). The QFT model of the strong force is quantum chromodynamics (QCD); and the combination of QED, QFD and QCD is the Standard Model [58]. The gravitational force is accurately modeled with the theory of general relativity, but general relativity is not a QFT model. There is currently no QFT model that combines the Standard Model with general relativity. For more about the problem of unifying the Standard Model with gravity, see [26].

Emmy Noether discovered the fundamental relation between the symmetries of a physical system and its conservation laws [41]. She proved this result in 1915 and published it in 1918. Her result had a profound impact on the development of modern physics. Each of the four types of force has a corresponding group of symmetries. The symmetry groups occurring in elementary particle physics are known as Lie groups, which are named after Sophus Lie who laid the foundations of the field. A Lie group is a group that is also a differentiable manifold and for which the operations of multiplication and inverse are differentiable. The underlying manifold of a Lie group is most commonly either a real manifold or a complex manifold, but other kinds of manifolds have been defined. Lie groups include the "classical" Lie groups, which consist of the orthogonal groups $O(n)$, unitary groups $U(n)$, and symplectic groups $Sp(n)$, as well as the five "exceptional" Lie groups, G_2, F_4, E_6, E_7 and E_8. The subgroup of an orthogonal or unitary group consisting of matrices with determinant 1 is called the "special" orthogonal or unitary group, written $SO(n)$ and $SU(n)$. There are also Lie groups for spaces that have time dimensions as well as ordinary spatial dimensions. When a Lie group has more than one connected component, the component containing the identity element of the group is indicated with a superscript plus sign.

Elementary particle physics models are expressed in terms of the symmetry groups for conservation laws that hold exactly or approximately. When a model is proposed for a physical phenomenon, it will generally be expressed in terms of a Lie group and its representations. We will see many examples of this. In this section we begin by discussing the Standard Model, and we then consider some of the extensions of the Standard Model that have been proposed.

Standard Model

The Standard Model was developed by large collaborations of thousands of physicists over the course of the second half of the twentieth century. This model is one of the most successful scientific theories of all time. The Standard Model has classified all known elementary particles, has made predictions of properties of particles with great accuracy, and has withstood numerous tests.

The symmetry group of the Standard Model is $SU(3) \times SU(2) \times U(1)$, where the three groups in the product correspond to the strong, weak and electromagnetic forces, respectively. These groups are called *gauge groups*, and the forces are called gauge forces or gauge interactions. The name "gauge" refers to the measurement of a quantity that remains invariant when a gauge group symmetry is applied to a physical system. The symmetry group of gravity is the Lorentz group $SO(3,1)$, the group of all homogeneous isometries of Minkowski spacetime. Minkowski spacetime is the four-dimensional model that combines the three dimensions of ordinary space with one-dimensional time. Various QFT models have been proposed for gravity, and this is an active area of research known as quantum gravity.

In the mid-1980's Wilczek and colleagues proposed QCD which is an improvement on the author's thesis [53] as it created a QFT model with quarks and gluons as fundamental particles. The breakthrough for the model of Wilczek and colleagues was the discovery of asymptotic freedom; namely, that some gauge forces become asymptotically weaker as lengths decrease and energies increase. As a result, it can happen that particles that are very close to each other paradoxically act "freely" when one would expect that the force would be so strong that the particles would have no freedom at all. QCD is a natural progression within QFT, where asymptotic freedom is described for short range forces [47]. Wilczek, Gross and Politzer received the Nobel Prize in 2004 for this discovery [63]. Several of the bosons in the author's Ph.D. thesis are now modeled as resonances of combinations of quarks, gluons and other new particles in the Standard Model of physics today. One important distinction between the Standard Model and quantum gravity is that the Standard Model is a renormalizable QFT model, while quantum gravity models are non-renormalizable [56].

The Standard Model includes the strong, electromagnetic and weak forces, but does not include gravity [15, 22, 63]. Figure 1 shows the elementary particles of the Standard Model. The elementary bosons consist of the photon, eight gluons, two W particles and the Z particle, all of which have spin 1, along with the Higgs which has spin 0. All elementary bosons, except for the W bosons, are the same as their antiparticles. The two W particles are a particle-antiparticle pair. There are 24 elementary fermions, each of which has spin 1/2: six quarks (up, down, strange, charm, bottom and top) and six leptons (electron, electron neutrino, muon, muon neutrino, tauon and tauon neutrino), along with the corresponding antiparticle of each of these.

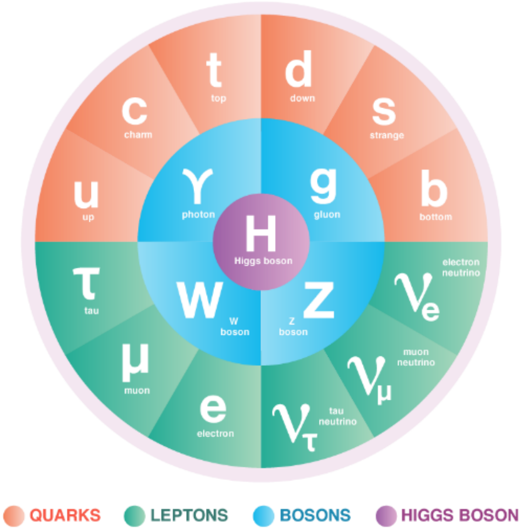

Figure 1: Standard Model Particles [63]

The elementary bosons are the force carriers: the photon carries the electromagnetic force, the W and Z particles carry the weak force, and the gluons carry the strong force. These bosons are called vector bosons because they correspond to vectors in the adjoint representation of the symmetry group of the force that they carry. The adjoint representation of $U(1)$, the symmetry group of QED, has dimension 1, and the photon is the only force carrier of electromagnetism. Similarly, the adjoint representation of $SU(2)$, the symmetry group of QFD, has dimension 3, and there are three force carriers of the weak force; namely, the two W particles and the Z particle. The adjoint representation of $SU(3)$ has dimension 8, and there are eight gluons. The Higgs boson is the only elementary boson that is not a vector boson. The Higgs is a scalar boson, so called because it transforms like a scalar under Lorentz transformation, i.e., the Higgs is Lorentz invariant.

Other than the force carriers, the particles of the Standard Model are either hadrons or leptons. The hadrons are composite particles made of quarks, and the leptons are elementary particles. There are six quarks, each of which has a corresponding antiquark. Hadrons are categorized into two families: baryons and mesons. Baryons are made of an odd number of quarks, and mesons are made of an even number of quarks. The most common hadrons are protons and neutrons which are constituents of atomic nuclei. A proton is a baryon that consists of two up and one down quark; a neutron is a baryon that consists of one up and two down quarks. All hadrons are unstable, with the possible exception of the proton. While the proton is stable in the Standard Model, there are some extensions that predict proton decay, albeit with a very long half-life. The term "parton" is used for quarks and gluons, so called because quarks and gluons are the parts of baryons [44].

As one would expect, by Noether's theorem, symmetry groups and their representations play an important role in the Standard Model not only for the force carriers but also for quarks, hadrons and leptons. As explained in [47]:

> The full Standard Model gauge group is SU(3) × SU(2) × U(1). Leptons, Higgs, and electroweak gauge fields are color SU(3) singlets. The vector particles corresponding to the SU(3) gauge field are referred to as gluons and the quantum number carried by the quarks is color. Hadrons (baryons and mesons) can be regarded as composite bound states of quarks and gluons (Figure 2). However, neither quarks nor gluons have ever been observed as free particles; they appear to be permanently confined in hadrons that transform as singlets with respect to SU(3). This is due to nonperturbative effects that can be calculated roughly but the physical mechanism for which is still not fully understood. Nevertheless, a careful analysis of QCD as a renormalizable field theory shows that the strong coupling constant runs with the energy scale of a process. It is very strong for scales $< 1\text{GeV}$, resulting in the binding of the quarks and gluons into composite states. However, it grows weaker with increasing scales (asymptotic freedom), and for processes involving energies much higher than 1GeV, perturbation theory in terms of the quark and gluon states is applicable, which allows detailed comparison with experiment.

Experimental techniques relating to the Standard Model particles and beyond are summarized in an eBook as lecture notes [23].

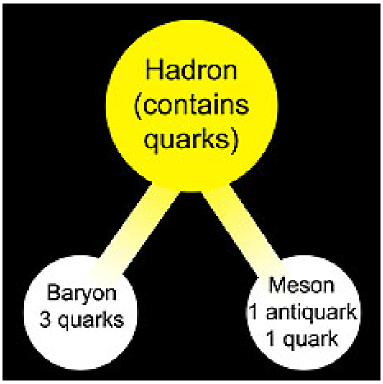

Figure 2: Hadrons include baryons (e.g., neutron, proton) and bosons (e.g., mesons)

Extensions of the Standard Model

In spite of the great success of the Standard Model some physical phenomena are not yet explained by the Standard Model. We now give an overview of extensions of the Standard Model that have been proposed to deal with some of the open problems. In Figure 3, the Fundamental Physics at the Intensity Frontier 2012 [25] lists reports from topics that formed the basis for working groups, including experiments that probe (i) heavy quarks, (ii) charged leptons, (iii) neutrinos, (iv) proton decay, (v) light, weakly interacting particles, and (vi) nucleons, nuclei, and atoms.

There are many articles relating to multi-dimensional spaces, such as group representation spaces, on particles and nuclei as well as theoretical papers dealing with elementary particle physics and cosmology. These go deeper in connections between physics and mathematics. For example, the QCD being able to predict quarks and gluons (Wilczek) of the Standard Model of particle physics can be described with 8 dimensions [63]. Others tie the electroweak (Weinberg and Salam), nuclear and electromagnetic forces require up to 11-dimensional space. The following paragraphs provide a glimpse [20].

The Fock space is the quantum state space of a variable or unknown number of identical particles from a single particle Hilbert space [18]. The second quantization formalism introduces the creation and annihilation op-

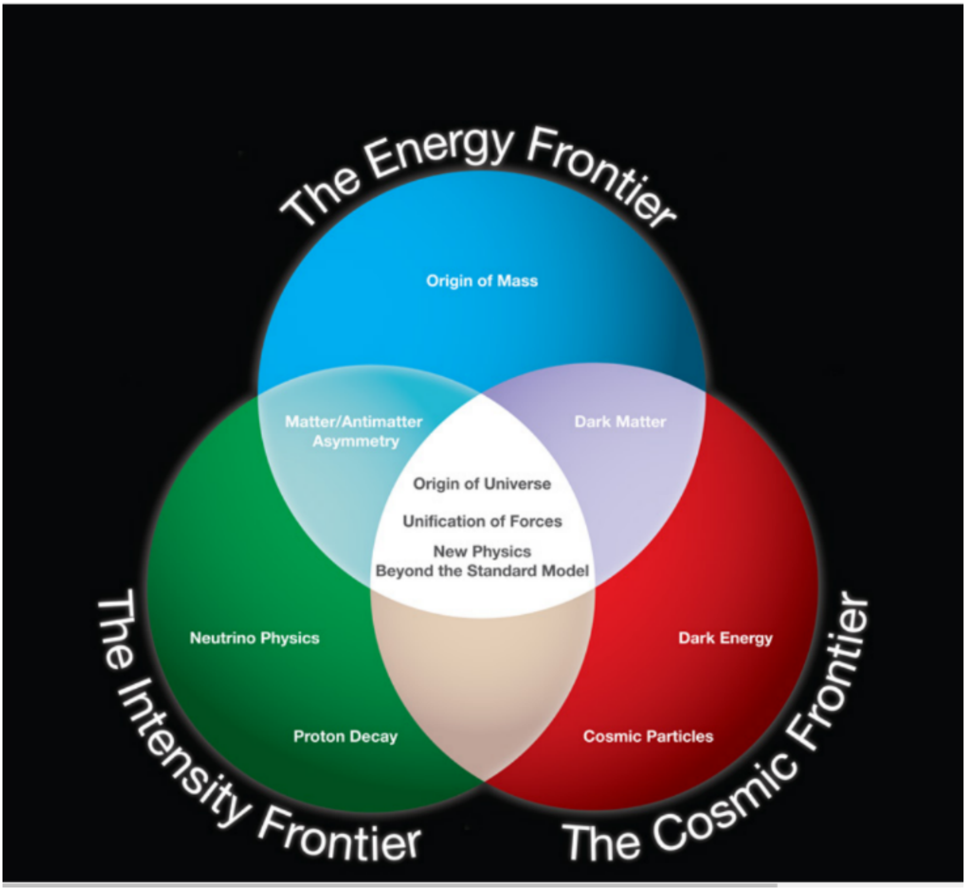

Figure 3: Fundamental Physics at the Intensity Frontier 2012 [25, Figure 1-1]

erators to construct and handle the Fock states, providing useful tools to the study of the quantum many-body theory.

Mathematical extensions of Euclidean space to Riemann, Minkowski, Hilbert space (e.g., Dirac and Fock space) and beyond go on increasing the dimensionality as many supersymmetry (SUSY) considerations and publications show. Further, Kaluza-Klein and other modifications and extensions of multi-dimensional spaces are leading to comparisons of the cosmological constant, are often in disagreement and depend on how dark matter and dark energy are to be accounted for. It has been shown that (a) it is possible to unify general relativity with the Weinberg-Salam theory of electroweak interactions in the framework of a 7-dimensional geometric model, and (b) the unification of general relativity and classical chromodynamics is possible in the framework of an 8-dimensional geometric model [60].

Various subalgebras have been proposed as the gauge groups of the most common Grand Unification Theory (GUT) models, including $SU(5)$, $Spin(10)$, and $SU(4) \times SU(2) \times SU(2)$. Lorentz and conformal spacetime symmetries are also found within EIX, one of the three real forms of the exceptional Lie group E_8. The 128-dimensional Majorana-Weyl spinor representation from $EIX/Spin(12,4)$ allows for an efficient way to encode three generations of the Standard Model fermions [11, 57]. This latest work related to GUT proposes six-dimensional spinors, and a $Spin(3,3)$ symmetry to describe all three generations of fermions as well as hypothetical X and Y bosons that are analogous to the W and Z bosons of the Standard Model. This GUT relates well to Minkowski and pseudo-Riemannian spaces [39].

The relationship between 11-dimensional spacetime and SU groups, spinors, etc., for GUT using Riemannian spacetime with local Lorentz symmetry $SO^+(3,1)$, and a 7-dimensional sphere S^7 which compactifies the remaining seven spatial dimensions shows how multi-dimensional considerations are being used in particle physics. The proposed extension predicts baryon-lepton conserving nucleon decay, via X-boson exchange as in other GUTs. Other physical consequences are lepto-quark mixing [56].

However, when combining them in the product group $SU(4) \supset SU(3) \times U(1)$, and then by combining all groups into $SU(2) \times SU(4)$, one gets a combined symmetry scheme that seems to support unification by the group $SU(8)$. It is found that the smaller $SO(4)$ group, instead of $SU(4)$, also seems appropriate for achieving unification, and it offers the advantage that it simplifies the theory and reduces the number of gauge fields required [37].

The modern theory of SUSY is a theoretical multi-dimensional framework for which forces and matter are governed by the same equations. In a SUSY model each particle has a superpartner whose spin differs by a half-integer so that each fermion has a boson superpartner and each boson has a fermion superpartner. There are many SUSY models. So far no experiment has found any superpartner particles, but many theorists still use SUSY for describing particles beyond the Standard Model (BSM). Hence, one can expect SUSY to be relevant in particle theories as these approach matter-energy from known forces, including gravity.

Effective Field Theories

Effective Field Theories (EFTs) and other multi-dimensional space related studies are trying to address GUT and BSM. An EFT is a technique for describing physical phenomena at a longer length scale, while ignoring behavior at smaller scales by averaging the smaller scale behavior. The intention is to develop a more tractable, but still accurate, model at the longer length scale.

Soft-collinear effective theory is a popular framework that is used to describe Higgs physics, jets and their substructure, as well as more formal problems [31]. The EFT framework is ideal for handling gravitational radiation emitted at the inspiral phase of binary compact objects, such as black holes. Cosmology is inherently a cross-cutting domain, spanning scales over about 10^{60} orders of magnitude, from the Planck length to the size of the observable universe. In the formidable open questions in physics that still lie ahead, EFT is likely to play an important role.

High Luminosity LHC

Luminosity is an important indicator of the performance of a particle accelerator: it is proportional to the number of collisions that occur in a given amount of time. The higher the luminosity, the more data the experiments can gather to allow them to observe rare processes [33]. The High-Luminosity LHC (HiLumiLHC), which should be operational from the beginning of 2029, will allow physicists to study known mechanisms in greater detail, such as the Higgs boson, and observe rare new phenomena that might reveal themselves. For example, the HiLumiLHC will produce at least 15 million Higgs bosons per year, compared to around three million from the LHC in 2017.

The HiLumiLHC project was announced as the top priority of the European Strategy for Particle Physics in 2013. The project is led by CERN with the support of an international collaboration of 44 institutions in 20 countries – the vast majority in various European countries among which Italy, Spain, Sweden and the UK – as well as a number of CERN's non-member states such as the United States, Japan and Canada.

During proton collisions at the LHC, many particles, including the carriers of the electroweak force – photons and W and Z bosons – are produced. Vector boson processes are an excellent probe to seek deviation from theoretical predictions. Two rare processes that are of particular interest as they probe the self-interactions of four vector bosons are diboson production via vector boson scattering and triboson production. The observation and measurement of these processes are important as they test the electroweak symmetry breaking mechanism [33]. At the LHC physics conference in 2020, the ATLAS and CMS collaborations presented new results relating to a vector boson scattering. CMS also reported the first observation of triboson production. Studying these processes to test the Standard Model is important as it could shed light on new physics. In addition, resonances of potential scalar particles are conjectured in the 95, 151 and 670 GeV regions, based on LHC data [32].

Future BSM Investigations

One of the significant BSM activities relates to understanding the electroweak interactions. Since the Standard Model includes three forces, the integration of these in the Standard Model implies correlations and transformations among particles as carriers of these forces or as products of them. Relating to weak forces are not only W and Z bosons but also three types of neutrinos, and quark, gluon and photons interplay. Many resonances and mesons as well as electrons and photons also interact. The more we understand the interplay and products of such interactions, including their properties such as spin, charge, flavor, parity, spin, and masses, the better we are able to construct a model; and it appears that for integrated understanding in the Standard Model and beyond with new resonances and hopefully somewhat more stable combinations, we will then be able to understand the interactions of gravity as well. Hence it is crucial to understand electroweak interactions, particle resonances and neutrinos. The conjectured Majorana nature of neutrinos and the masses of neutrinos are important goals of future experiments [2]. Also, diboson, triboson and Higgs doublets are exposing new BSM as we speak!

As one can see from this whirlwind tour of proposals for extensions to the Standard Model, it is important in particle physics to have an understanding of Lie groups and multi-dimensional spaces.

Nuclear Physics

There are various models proposed for the atomic nucleus and used in several experiments. These include liquid-drop and shell models. In this overview of current nuclear theories, nearly 60 years after the author's Ph.D. work in nuclear particle physics [24, 53], even today the best observed elastic scattering data conform to a shell model description of the atomic nucleus. There are numerous recent papers referenced here that describe this model. For example, Breit and Wigner gave the famous reaction cross section for nuclear resonances [8].

Nuclear interactions are inclusive of scalar, pseudoscalar and vector fields that exchange bosons [9, 28, 48, 49]. The formalism is based on the Einstein-Podolsky-Rosen formalism [17] extended by Green and Sharma [5, 7, 21]. It may be related, but this formalism is not the same as the Einstein-Podolsky-Rosen paradox for quantum entanglement. The field equations of the formalism are based on Fock space, Dirac-Fock QFT formalism, and Breit's reduction to large components for fundamental nucleon-nucleon force through boson exchanges [53]).

This theory was applied to create nuclear models where nucleon-nucleon interaction was described with one-boson-exchange. All available elastic scattering data below 400 MeV energy were explained through phase shifts. The limitations were in modeling the deep interior of the nucleus and needed a cutoff radius and the assumption of elastic scattering; namely,

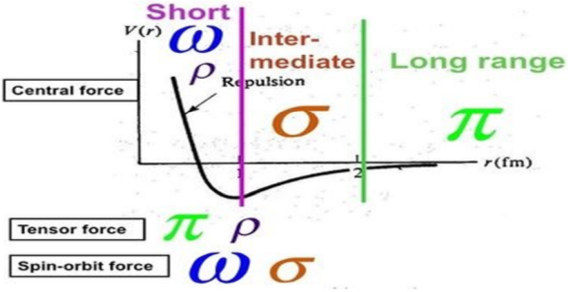

Figure 4: The strong nuclear force acts differently in each of the three distance ranges shown in this figure, and the force intermediaries differ depending on the distance range. [34, 35]

no particle production such as π mesons was occurring [9, 49]. Later work by Haracz and Sharma included two-boson-exchange models [24].

While the QCD was proposed in the 1980's, the Nobel Prize for quarks and gluons was awarded in 2004 to Wilczek, Gross and Politzer, which established the Standard Model especially with observations from LHC [63]. These would form an enhancement to the understanding of the structure and composition of the nucleus beyond not only electrons, protons and neutrons, but also redefine many of the bosons that are today reinterpreted as resonances formed from constituents of Standard Model particles such as quarks and gluons relevant to strong nuclear forces [53].

For example, Machleidt in [34, 35] shows that quarks, gluons and one-boson-exchange as well as the shell model descriptions fit the current nucleon-nucleon scattering data. Figure 4 shows the nuclear force as a function of distance and the primary force intermediaries for each distance range. Nucleon-nucleon scattering experiments in the region up to GeV and TeV energies using LHC, with CMS, ATLAS and other high luminosity experiments have so far produced resonances and particles numbering over 100 as we speak. In parallel, observationally in astrophysics, photons and spacetime dimensions are used to determine properties of nuclear constituents.

Recent work at the Jefferson Lab of the US Department of Energy has studied various theoretical and experimental aspects of nuclear

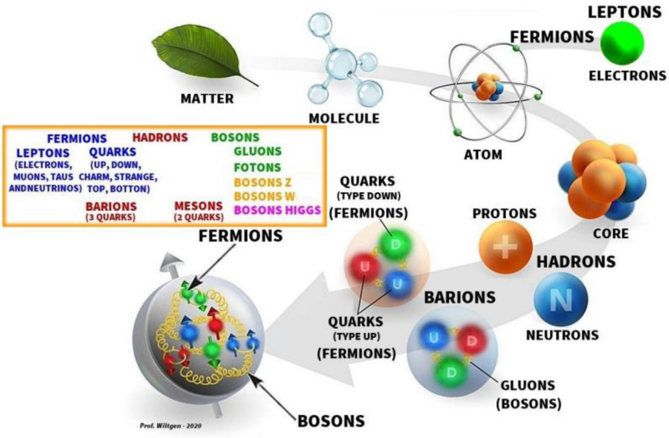

Figure 5: Expanded nuclear force contributors from the Standard Model. [64]

structure. The most recent studies include traditional one-boson-exchange potential and inclusion of QCD components, the most important being partons and their nuclear force effects including mass effects in bound nuclei, for example, up, down, and strange quarks. Review papers take us to the structure of the nucleus from Rutherford to QCD based nucleon-nucleon scattering. Just to advance to recent nuclear theory including all the Standard Model particles Figure 5 is an expanded pictorial version of original image from the Jefferson Lab.

Other shell model references are [13] and [66]. As combinations of quarks and gluons form different states of nucleons, especially at high energies, the shell structure becomes complex and relativistic, and inelastic processes occur. Such studies are described in reference [46]. As nuclei have increasing p, n numbers, their models using QCD become complex and such studies are extensive and recent using proton beams, photons, and ions. Example references using modified shell models include [52, 59].

The liquid-drop model also explains many observations and similarly there are models that are akin to gas and ionized media as in atoms, and some use Hartree-Fock formalism [33, 43, 62]. The liquid-drop model reproduces masses of stable nuclei very well [55].

A variety of symmetry-based nuclear models have also been developed in nuclear physics [65]. It is amazing to see effects of symmetry breaking and restoration and group theory in Wigner's work, in Hartree-Fock-Slater and related spaces [8, 18, 53], in nuclear structure largely concentrating on shell models of nuclei and their spectra and efforts at simplifying the nuclear many-body problem.

This study [67] illustrates the interplay of Standard Model particles (quarks) in nuclei which were earlier thought of as bound states of nucleons and describes the energy dynamics of quarks in quark-meson coupling (with a spherical bag containing 3 quarks with mass about 5 MeV) and by confinement of quarks in a harmonic oscillator field as an alternate theory. For nuclear matter, the bag decreases the binding energy and increases the symmetry-energy. For a neutron star the bag affects the radius of a 1.4 solar mass star significantly, with the maximum mass only slightly modified.

A very recent paper encompasses complexities of nuclear structure beyond a shell model description, with the conclusion that atomic nuclei are surprisingly richer objects than initially thought [42]. How the increasing the number of protons and neutrons affects complex nuclei, indicating that complex shell and multiphase implications in nuclei growth is indicated. It emphasizes that understanding nuclear structure requires not only determining the basic internal structure of the nucleus in terms of fundamental particles but also determining what happens as more nucleons are added to create the "wealth" of nuclear phenomena.

Atomic nuclei are surprisingly richer objects than initially thought [42]. Consequently, we need to go beyond the picture of the solid potential well by activating the monopole interactions of the nuclear forces. This produces notable consequences in key features such as the shell/magic structure, the shape deformation, the dripline, etc. These consequences along with emerging concepts such as shell evolution, T-plot, self-organization (for collective bands), triaxial-shape dominance, a new dripline mechanism, and many others are likely to have a significantly impact on our understanding of nuclear physics.

Dark Matter

As early as 1884, physicists and astronomers were speculating that there were unseen bodies in the universe. However, it was not until the

1960s that the first concrete evidence of dark matter (DM) began to be reported; namely, the anomalous galaxy rotation curves. As more and more evidence was found, there began a search for the exact identity of DM. Speculations were so varied that some students created a whimsical flowchart of the "algorithm" for DM research [30]. For a somewhat more serious flowchart see [16]. Since then international consortia have developed roadmaps to help direct research activities in this area. In this section we provide references on theories, results and related examples on DM studies, plans, particle colliders and astrophysical observations, as well as selected quotes from references. One of the prevailing trends is that if we can keep refining the particles and resonances in the Standard Model and beyond, then perhaps we can discover and understand DM related physics. Another parallel trend is to keep refining observations in astrophysics to discover properties of matter-energy in the universe and piece them together to understand the nature of and the limits on DM.

The following is from the Elementary Particle Physics Vision for European Parliament 2024 [45]:

> The nature of DM is a major question whose solution is necessarily outside the Standard Model, and which need not be connected to the Higgs. It is very important to find direct evidence for the particle nature of DM. The idea that DM is a particle with mass at the Higgs boson mass scale is now strongly challenged by experiment. Such heavier weakly interacting massive particles (WIMPs) – together with axions, which are also particles of the Higgs sector – are the best-motivated DM candidates today. Models of flavor, baryogenesis, and neutrino mass all are built on hypotheses for the Higgs sector. Because we do not yet have a Higgs principle, these models cannot be predictive.

Current observational constraints permit the mass of a DM particle to range from 10^{-22} eV to 10^{48} GeV [50]. In other words, a DM particle could be as small as 10^{-22} times the mass of an electron or nearly as large as the mass of the Moon. Terrestrial studies of neutrons and nuclei play a key role in the interpretation of cosmological tests. We now discuss some of the research related to DM.

Dark Matter Searches at CMS and ATLAS

A large variety of interesting DM signatures are currently being covered by ATLAS and CMS. Five of the latest DM searches carried out by both collaborations were presented. None of these analyses found evidence of DM production at the LHC. Nevertheless, the huge amount of data still to come, the analysis improvements envisaged, and the new search proposals planned in the near future, confer a strong incentive to continue the hunt for DM at the LHC [1].

The number of hadrons that are now known is over 70. Regarding the rapid and continuing discoveries, Quigg recalled Rutherford's conclusion to his lectures on the nucleus (ca. 1925) "It's all right, don't worry, we haven't discovered it all; much remains to be done." to which Quigg added "We haven't even thought of it all!" [49]. Further, Powell (1950) on Occhialini's emulsions from Pic du Midi said,

> It was immediately apparent that a whole new world had been revealed … It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished, and all kinds of exotic fruits had ripened in great profusion.

Figure 6 gives a pictorial representation of many of the hadron resonances.

Dark Matter Flowchart

DM is a mystery and gravity considerations estimate it to be invisible matter consisting of around 26% of the mass-energy in the universe while around 68% is related to the acceleration of the universe, the so-called dark energy. This means what we see from the Standard Model is only around 5% of the mass-energy in the universe. The DM flowchart [16] takes one through various options related to gravity and particle aspects of DM, for example Modified Newtonian dynamics, tensor-vector-scalar modifications to Einstein formalism and differential space and time warping. Thus, one is steered to some form of invisible matter which has many proposed varieties and versions. These include Massive Compact Halo Objects, such as white dwarfs, neutron stars, black holes. These do not explain the cosmic microwave background (CMB) or the Big Bang. Alternatively, one considers unknown matter as DM candidates such as non-baryonic matter and therefore not being massive nor being atomic level matter. The

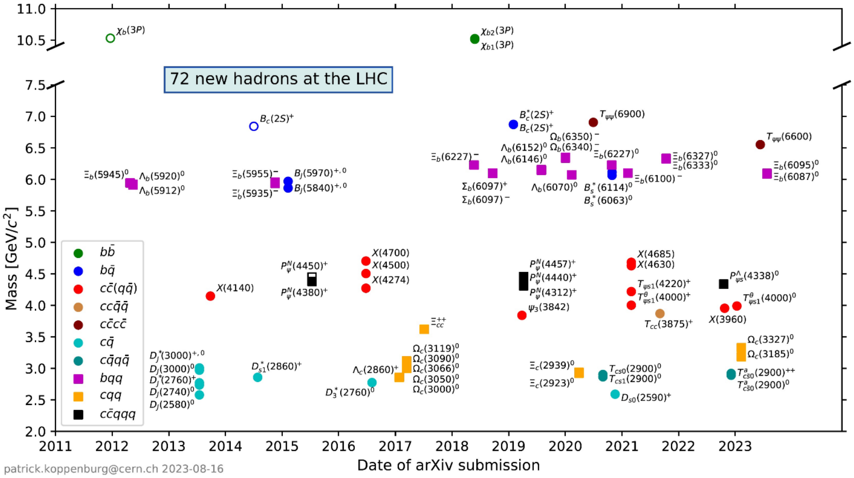

Figure 6: “Exotic Fruits” - All hadron resonances (2011–2023) from CMS [49]

possibilities for DM are classified according to the free streaming length as “hot”, “warm” or “cold”. One possibility for hot DM is a neutrino, whose mass has not yet been determined fully by the LHC. Further various SUSY options include a warm sterile neutrino as the right-handed partner to the known left-handed neutrino. The graviton itself has not yet been found so its SUSY partner gravitino is yet another possibility. Cold matter is appearing as favorable for DM candidates WIMP and axion. The former is heavier than a proton and the latter is a QCD compatible favorite that is yet to be confirmed. Light SUSY particles have also been proposed. The next sections look at these DM candidates and other proposals in more detail.

Dark Matter Candidates

WIMPs are hypothetical particles that are one of the proposed candidates for DM [61]. Working Group 5 of the Astroparticle Physics for Europe gives a roadmap for research on DM [10]. One path is the direct detection of a WIMP via heat, light and ionization in elastic nuclear scattering. Current experiments that are running, for example CDMS II and Xenon 10 have recoil energies in 20-100 KeV range and could detect a WIMP in the tens of GeV ranges. Three of the experimental lines include argon and xenon cryogenic detectors.

Axions were introduced to explain why charge conjugation parity symmetry is preserved in QCD. Wilczek named this new hypothesized particle the "axion" after a brand of laundry detergent because it "cleaned up" a problem, while Weinberg called it "the higglet". Weinberg later agreed to adopt Wilczek's name for the particle [6]. If axions exist and have low mass within a specific range, they are of interest as a possible component of cold DM.

Anyons are particles that can take any fractional spin, not just multiples of one-half like fermions and bosons [3]. Braiding 2d and 3d space, Fermi-Dirac and Bose-Einstein, and phase factor in exchange of particle wave functions, the search for anyons and fractional spins, as forecast by Wilczek and verified by French and Purdue groups, are taking us to deeper aspects of how these are related to Poincaré, Hilbert and other spaces. Thus, the situation of particles and their space-dimensions are an unresolved canvas.

> In much the same way that two fermions (e.g., both spin 1/2) can be looked at together as a composite boson (with total spin in a superposition of 0 and 1), two or more anyons together make up a composite anyon (possibly a boson or fermion). The composite anyon is said to be the result of the fusion of its components [49].

Argüelles argues that DM is fermionic but that the differentiation between bosons and fermions occurs after energy quanta are created [5]. They propose DM in galactic centers are dominated by fermionic DM. In his thesis Masi proposes that DM [38]:

1. is dark, i.e., it has a zero electromagnetic cross section;
2. cannot be seen in an accelerator through its annihilation products;
3. are thermal relics, which would imply, without new contributions, that DM particles should have a mass that is less than 1 TeV;
4. annihilates in pairs into Standard Model particles;
5. is a stable and simple particle.

These properties of DM can be established only by the combined effort of astronomy, space and laboratory experiments.

Astrophysics and Dark Matter

The Scotogenic DM model proposed that WIMP scattering could be observed when the resulting neutrino production gets absorbed and produces Cherenkov radiation. Attempts to detect this radiation in the IceCube Neutrino Observatory in Antarctica did not find any conclusive evidence [9]. An extension of the Standard Model, scotogenic means "darkness offspring" and roughly relates to WIMP annihilation in the Sun.

Recently the Theoretical Advanced Study Institute Lectures on the Particle Physics and Astrophysics of DM discuss DM in galaxies and DM models, higgsinos and minimal DM [51]. The study claims to set the stage for DM discovery over the next decade or so. This paper estimates the DM particle axion density in the Milky Way galaxy, and also proposes estimates based on Bayesian statistics.

Perhaps the most divergent suggestion is that there may not be any DM at all or at least not very much. A significant number of physicists have proposed alternative explanations for the anomalous behavior of the distribution of masses in galaxy arms. These alternative explanations reduce or eliminate the need for massive amounts of unseen matter. The explanations are theories known as Modified Newtonian Dynamics (MOND). A MOND theory proposes a modification of the current model for the dynamics of objects that are subject to very small gravitational forces and consequently very small accelerations as is the case at galactic scales [19].

Physics beyond the Standard Model

We now have a large list of particles [32], both confirmed and hypothesized. In the remainder of this section, we give a brief overview of the research activities in physics after the discovery of the Standard Model particles that would have a bearing on DM. While combinations of Standard Model particles at high energies yield or indicate new physics, more resonances and fast decaying particles are being found, predominantly at LHC and other colliders, as well as using Standard Model knowledge to understand cosmology with newer space based (and ground) telescopes and detectors. Studies are also concentrating on GUT by trying to see what is missing and to incorporate the gravitational force.

Partons are described by their distribution functions [27]. The

NNPDF collaboration, determines the structure of the proton using contemporary methods of artificial intelligence [40]. A precise knowledge of the parton distribution functions of the proton, which describe their structure in terms of their quark and gluon constituents, is a crucial ingredient of the physics program of the LHC. It has played an important role in the discovery of the Higgs boson. Its incomplete knowledge is one of the main limitations in searches of new physics.

Singh has proposed a 16-dimensional-space based model that is claimed to unify the standard model with gravitation [54]. In other words, this would be a Theory of Everything (TOE). This proposed model uses the octonions, a kind of hypercomplex number system. The symmetry group is $E_8 \times E_8$. In addition to the four known forces, this new model predicts two new forces and provides a theoretical justification for MOND.

A Gamow state is a vector state for the pure decaying part of a quantum resonance. It has been claimed that when resonances and Gamow states are present a Bose-Einstein condensate (BEC) is precluded [12]. BEC is relevant to DM searches because of the possibility that BEC ultralight bosons could be DM candidates [29].

DM research is highly multidisciplinary, applying methods from many disciplines of physics, including classical, statistical and quantum mechanics, thermodynamics, relativity, nuclear and particle physics, astrophysics, and cosmology. The many DM hypotheses are one part of the puzzle of modern physics.

Conclusion

I hope this tour of has conveyed some of the excitement and the wealth of research, speculation and activities that abounds today in elementary particle physics, nuclear physics and DM research. This article is the first of a series. Later articles will examine physics from other points of view, especially history and philosophy.

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Glossary

ATLAS The largest general-purpose particle detector experiment at the LHC. At present, the ATLAS Collaboration involves over 6,000 members from 257 institutions in 42 countries.

BEC Bose-Einstein condensate

BSM Physics beyond the Standard Model

CERN European Organization for Nuclear Research

CMB Cosmic microwave background

CMS Compact Muon Solenoid at the LHC. The CMS Collaboration involves over 4,000 members, representing 206 institutes and 47 countries.

DE Dark Energy

DM Dark Matter

EFT Effective Field Theory

eV The kinetic energy of a single electron accelerating from rest through a potential difference of one volt in a vacuum. The standard definition of eV is exactly $1.602176634 \times 10^{-19}$ Joule.

EWT electroweak theory

Fock space The completion of the direct sum of the symmetric or antisymmetric tensors in the tensor powers of a single-particle Hilbert space. The Fock space is used for constructing models of systems with many particles of the same type.

GUT A Grand Unified Theory is any model in particle physics that merges the electromagnetic, weak, and strong forces into a single force at high energies.

Hilbert space A vector space equipped with an inner product that induces a distance function for which the space is a complete metric space.

LHC Large Hadron Collider at CERN, the world's largest and highest-energy particle collider.

MACHO Massive Compact Halo Object

MOND Modified Newtonian Dynamics

O(n) The orthogonal group is the group of distance-preserving transformations of a real or complex Euclidean space of dimension n that preserve a fixed point.

O(p,q) The orthogonal group is the group of distance-preserving transformations of a real space with p spatial dimensions and q time dimensions, and that preserve a fixed point The orthogonal group for Minkowski spacetime is O(3,1).

Planck length The length below which the SM and general relativity are not applicable because the models are not meaningful mathematically. It is approximately equal to 1.616×10^{-35} m. Another way to understand the Planck length is that the only way that one can observe phenomena at a given length, at least with current techniques, is to use probes whose energy is inversely proportional to the length. At the Planck length the energy is so high that black holes would be produced, effectively making observation impossible.

QCD quantum chromodynamics

QED quantum electrodynamics

QFD quantum flavourdynamics

QFT quantum field theory

Representation A way of expressing the elements of a group as linear transformations in a vector space. A group typically has many inequivalent representations, and the quantum states of an elementary particle are related to the representations of its symmetry group.

Spin(n) The spin group is a group whose underlying manifold is the double cover of the special orthogonal group SO(n).

Spin(p,q) The group whose underlying manifold is the double cover of the special orthogonal group SO(p,q).

SUSY supersymmetry

TOE A Theory of Everything is any model that integrates all four forces: the electromagnetic, weak, strong and gravitational forces.

U(n) The unitary group of $n \times n$ unitary matrices.

WIMP weakly interacting massive particles

DR. RAVI SHARMA is a Senior Enterprise Architect. Dr. Sharma is an industrial entrepreneur, theoretical nuclear and particle physicist, human space systems scientist, fuel cell and hydrogen technologies specialist, satellite remote sensing and image data systems specialist. He has held significant positions in Academic, Government, Industry and R&D Organizations in the US and India. He has received the NASA Apollo Achievement Award.