

Forging the Inner Space - Outer Space Connection

by

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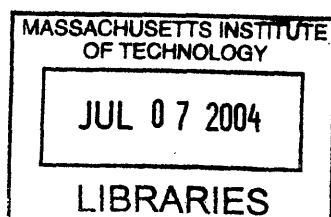
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Abstract

In this thesis, I discuss the Brans-Dicke theory of gravitation, the Higgs mechanism, and the relevance of these two theories to the bridging of cosmology and particle physics. Although the former theory is in the field of cosmology while the latter is in particle physics, their similarities are impressive. Both attempt to understand the origins of mass. Even more striking is the mathematics involved in each of these theories. The Brans-Dicke theory and the Higgs mechanism both introduce a new scalar field that is coupled to matter in the universe. Although these theories were formulated around the same time in the early 1960s, are so similar in motivation and method, and became quite popular in their own respective fields, they remained relatively unknown outside of their field for quite some time.

In this thesis, I have summarized both the Brans-Dicke theory and the Higgs mechanism. Then, I have analyzed the number of articles citing the Brans-Dicke and Higgs papers to understand when particle physics and cosmology first began integrating. To extend this further, I have looked at how many articles in 1961, 1971, 1981, and 1991 can be categorized as both particle physics and cosmology. In conclusion, we see that the two fields were slow to build common ground, although this has improved since the 1980s. By the 1990s, collaboration between particle physics and cosmology had greatly increased, most likely because of attempts to unify gravity with the other three forces.

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A hundred times every day I remind myself that my inner and outer life depend on the labors of other men, living and dead, and that I must exert myself in order to give in the same measure as I have received and am still receiving. —Albert Einstein

This thesis is the culmination of my physics experience at MIT - and what an experience it has been. I came to this school in love with physics. I am leaving this school even more in love with physics. I knew this was my last chance to do a subject I enjoy so passionately. My decision to pursue a career in Public Health is for reasons that would not exist in an ideal world - my heart will always be with physics, the subject that I have studied for the last four years at MIT. The beauty of physics can only be matched by the beauty of those who have helped me along the way.

My family, well, they are amazing. Their constant and endless support is priceless. Perhaps my mother, father, and brother will never fully realize just how important they are to every success I have ever had. Nonetheless, their contribution to my life has made me who I am. Without them, I would not be here. Any accomplishment I have had is theirs - they are the world to me.

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And now, I leave you with one of the better physics jokes I've heard during my time at MIT:

A bar walks into a physicist. Oops, wrong frame of reference!

Sincerely,
Shefali Oza

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Chapter 1

Introduction

While the entire twentieth century has been very important for the advancement of physics, the 1960s were especially relevant for theories pertaining to the origin of mass. In particular, two theories during that decade have had long-term effects on the physics community. In the field of cosmology, Carl Brans and Robert Dicke in 1961 formulated an alternative theory to Einstein's general relativity that has caught more attention in the physics community than almost any other such theory. Similarly, Peter Higgs' 1964 formulation of the Higgs mechanism in particle physics to explain how particles acquire mass has had a tremendous impact in the field of particle physics for the last forty years.

In terms of differences, the fields themselves were quite distinct in the 1960s. Cosmologists and particle physicists did not share their thoughts on common physics issues, and thus the theories were kept in very separate circles for many years. Brans and Dicke used cosmological arguments, including general relativity, to formulate their theories. On the other hand, Higgs focused entirely on making his theory applicable to particle physics ideas of the time. In addition, the Brans-Dicke theory of gravitation has been essentially ruled out by experiment since the late 1970s, while the Higgs mechanism continues to play a major role in the Standard Model of particle physics.

Although the two theories are quite different, their similarities are quite astounding. As mentioned, each theory has attempted to explain the origins of mass. In doing so, both the Brans-Dicke theory of gravitation and the Higgs mechanism have applied common physics, namely introducing a new scalar field into their theories, to answer the question of mass creation. In addition, although the Brans-Dicke theory is no longer considered valid

while the Higgs mechanism continues to be accepted, both have had a major impact on physics. The Brans-Dicke theory of gravitation, as explained in chapter 2, has somewhat paradoxically popularized general relativity and helped to motivate technological advances in experimental equipment. On the other hand, the Higgs mechanism has yet to be tested but has similarly encouraged advanced experimental tools that will be implemented within the next few years in an attempt to verify the theory.

An important question to ask is why the two fields of cosmology and particle physics were so separated during the early parts of the twentieth century. In addition, an analysis of how and when they began coming together is a telling demonstration of how physics has evolved in the past half-century. Since the most cutting-edge theoretical physics involves ideas such as string theory, which intimately involve cosmology and particle physics, the merging of these two fields is highly relevant for current discussions of physics. A reasonable way to approach this question is to analyze the historical footprints that the Brans-Dicke theory and Higgs mechanism have left on physics since the 1960s. In addition, a general look at the categorization of published articles also offers a relevant perspective on this matter.

In this thesis, I will discuss the physics behind the two theories and then look historically at how the fields of cosmology and particle physics have slowly begun communication over the last quarter of a century. In chapter 2, I look at the Brans-Dicke theory of gravitation and use Einstein's theory of general relativity as a primer for this theory. The Higgs mechanism is examined in chapter 3 along with its significance to modern day particle physics. Then, in chapter 4, I discuss the historical analysis I have conducted to understand when the fields of cosmology and particle physics began to relate more to one another. Finally, in chapter 5 I conclude with a summary of what these historical trends indicate for the near future of these two fields and these theories that played such a large role in shaping the last forty years.

Chapter 2

Brans-Dicke Theory of Gravitation

Of the many alternative theories to general relativity that have been proposed in the last century, the Brans-Dicke theory of gravitation is one of the most important. This theory, proposed in 1961 by Carl Brans and Robert Dicke, attempts to uphold the fundamental principles of general relativity while making the equations compatible with Mach's principle. While the theory gained support through the 1960s and part of the 1970s, experimental evidence eventually confirmed the validity of Einstein's theory of general relativity over the Brans-Dicke theory of gravitation. However, the contribution of this latter theory to the field of physics, both directly and indirectly, has been significant. In this section, I will introduce the concepts of general relativity and Mach's principle that are crucial to the Brans-Dicke theory, and then provide more detail about the theory itself.

2.1 Introduction to General Relativity

Albert Einstein's formulation of general relativity in 1916 described an intimate connection between gravitation and spacetime. Unlike special relativity's focus on inertial reference frames, general relativity applies to all reference frames in the universe. This geometrical theory, validated theoretically and experimentally during the second half of the twentieth-century, is based on a metric tensor field. While having already established the connection between space and time in his theory of special relativity, Einstein's second theory suggests that gravitation is geometrically linked to spacetime. Although this theory was largely ignored during the early twentieth century because feasible experiments were lacking, general

relativity is now an important aspect of cosmology and other branches of physics.

Key aspects of the theory, explained in the following subsections, include the principle of equivalence and the curvature of spacetime. In addition, the field equations that come out of Einstein's theory are included.

2.1.1 Principle of Equivalence

Einstein's principle of equivalence, formulated in 1907, is the fundamental postulate of general relativity. This principle states that acceleration and gravitation are equivalent concepts. An experiment conducted within a uniformly accelerating reference frame will provide the same results as one conducted in a non-accelerating reference frame within a gravitational field where $g = -a$, at least locally, over an appropriately-sized region. About the principle, Einstein wrote [1]:

...we shall therefore assume the complete physical equivalence of a gravitational field and the corresponding acceleration of the reference frame. This assumption extends the principle of relativity to the case of uniformly accelerated motion of the reference frame.

In addition, unlike previous assumptions, the experiment can relate to any laws of physics that work within the frame of special relativity - not just mechanics. In fact, it is for this reason that the bending of light is explained. Since photons can have momentum even without mass, they are also affected by gravitational fields. Therefore, light too can be deflected in the presence of a gravitational field.

In other words, the Einstein's equivalence principle helped connect special relativity to gravity. Mainly, the principle established the notion that acceleration is relative, and that gravitation and acceleration act the same way (again, for local observers). While such a concept may seem simple, its consequences have been tremendous. Namely, the remaining aspects of general relativity, including spacetime curvature, branch from this principle.

2.1.2 Space-Time Curvature

A main argument of general relativity is that gravity results from the curvature of spacetime. The geometry of spacetime, which is not flat as was previously believed, is curved by the

presence of matter and energy. Therefore, non-Euclidean geometry is the necessary form of mathematical expression for some frames of reference within spacetime. Spacetime is a four-dimensional space in which masses create the curvature Einstein predicted in his theory.

As mentioned in the previous section, an important consideration of general relativity is that local frames must be limited to a small region of time and space. The frame cannot be indefinitely extended because the curvature of spacetime will dispel the assumed homogeneity within the frame. So, while the gravitational field over a long distance is not a static, homogeneous field, this approximation can be made for small regions of space and time. Therefore, special relativity can be applied to these ‘locally inertial frames’.

2.1.3 Field Equations

Einstein’s field equations can be written in the form [2]:

$$R_{ik} - \frac{1}{2}g_{ik}R + \Lambda g_{ik} = 8\pi\frac{G}{c^4}T_{ik} \quad (2.1)$$

In this equation, R_{ik} is the Ricci tensor. This tensor, which refers to the curvature of spacetime, is related to the full Riemann curvature tensor by a contraction, i.e. $R_{ik} = g^{ab}R_{iakb}$. If spacetime is flat, then this term goes to zero everywhere. Otherwise, curvature exists within the system. T_{ik} is known as the energy-momentum tensor of matter, or stress energy tensor. In his theory of general relativity, Einstein concluded that the energy tensors should be the ‘sources’ of gravity. R is the full trace of the curvature tensor, and g_{ik} is the metric tensor, which measures angle and distance in a space. This term is a 4x4 symmetric tensor, thus having ten independent terms. Since four spacetime coordinates can be freely chosen, these ten terms, and thus equations, become six. Therefore, there are 6 main equations to solve according to Einstein’s theory (when formulated in (3+1) spacetime dimensions).

Λ is the cosmological constant Einstein included into his field equations to make sure the solutions led to a static universe. While believing this was a huge mistake for the rest of his life, recent discoveries suggest that this term being non-zero is essential to satisfy some experimental and observational data. G is the gravitational constant that ranges back to Newton’s time and c is the speed of light.

These field equations show that the curvature, represented by R_{ik} , is directly related to the stress tensor, T_{ik} . Therefore, a main feature of these equations is that while matter tells space how to curve, space tells matter how to move.

Several physicists have proposed different solutions to Einstein's field equations. In fact, each of these solutions, such as the Schwarzschild and Friedmann solutions, have led to further physics in this area. Other solutions, such as de Sitter's empty universe, have challenged the postulates of general relativity, although in the end experimental results have continued to confirm the predictions of general relativity.

2.2 Mach's Principle

Mach's principle, credited to Ernst Mach for his ideas on the subject, states that concepts of rest and motion are irrelevant without a material background present somewhere in the universe. In other words, distant matter is required as a background in order to measure motion itself. For example, if the universe only contained one object, then nothing about this object's motion can be determined because its motion cannot be measured relative to any other object. So, physical quantities cannot be measured without other objects being used as references. Therefore, not only is matter necessary to understand motion, but local laws of mechanics inherently incorporate the existence of distant objects in the universe. Clifford Will writes [3]:

The notion is this: The inertial and gravitational properties of matter are in some sense linked to the existence of the rest of the matter in the universe.

A famous example of this principle is the hanging water bucket. Assume a bucket filled with water is hanging from a ceiling. The surface of the water within the bucket is flat. However, if the bucket is twisted around and around, then the water inside the bucket curves inwards. The age-old question, then, is: how does the water know it is rotating? Clearly, because of the change in surface, there is an effect on the water. While this example is as old as Newton, his conclusion that the water knows it is rotating relative to absolute space is unacceptable in terms of relativity and Mach's principle. Instead, a reasonable deduction is that the water knows it is rotating relative to the distant matter in the universe that is used as a background. Whether it is the bucket rotating in a non-rotating universe, or

a rotating universe rotating around the bucket is impossible to judge since all motion is relative [3].

2.3 Brans-Dicke Theory

Belief in Mach's principle was the fundamental inspiration for Brans and Dicke to formulate their own theory of gravitation. Although Einstein also believed strongly in Mach's principle and expected that general relativity would uphold it, later solutions to the field equations proved otherwise. Brans and Dicke attempted to make general relativity compatible with Mach's principle through their own theory. While most alternative theories to general relativity relied on ideas of flat spacetime, the Brans-Dicke theory was predominantly successful because it accepted curved spacetime and most of Einstein's general relativity. The main difference came in the addition of a scalar term to the tensor theory in order to uphold Mach's principle. This section looks at this theory in greater detail.

2.3.1 Overview

As mentioned above, the Brans-Dicke theory of gravitation is very similar to Einstein's theory of general relativity in many ways. For example, everything discussed in the previous section about the equivalence principle and the curvature of spacetime is included within the Brans-Dicke theory. The reason for this similarity is simple: Brans and Dicke agreed with the concepts of Einstein's theory, but they believed it failed because it did not hold true to Mach's principle. Their evidence of this was in de Sitter's solutions to Einstein's field equations in 1916. His solutions proposed an empty universe that were correct solutions to the equations [4]. However, an empty universe goes against Mach's principle, namely that matter is essential to understand the concept of motion or other physical quantities. Therefore, Brans and Dicke hoped that their alternative theory of gravitation would uphold Mach's principle, which they believed to be one of the most fundamental concepts about the universe.

2.3.2 The Changing Gravitational Constant, G

Perhaps the most important conclusion Brans and Dicke arrived at in order to satisfy Mach's principle was that the gravitational constant G must be changing in different regions of spacetime. In the end, they assumed that G would be proportional to the reciprocal of a scalar field. They came about this conclusion as follows:

Brans and Dicke looked at relations within solutions to Einstein's field equations that would provide a link between G and the large-scale structure of the universe. One relation they found with such properties was within the Friedmann cosmologies, which offer solutions to Einstein's field equations for an expanding universe. The relation is as follows [5]:

$$\rho_0 = \frac{3H_0^2}{4\pi G} q_0 \quad (2.2)$$

where ρ_0 is the rest-mass density of galaxies in the current epoch, H_0 is the Hubble constant and q_0 is the deceleration parameter. Substituting $R_0 = \frac{c}{H_0}$ and $M_0 = \frac{4\pi R_0^3 \rho_0}{3}$ as the characteristic length and mass of the universe, respectively, we arrive at the following conclusion [5]:

$$\frac{1}{G} = \frac{M_0}{R_0 c^2} q_0^{-1} \approx \frac{M_0}{R_0 c^2} \approx \sum \frac{m}{r c^2} \quad (2.3)$$

where m and r are the masses and positions of individual point sources.

With these equations, Brans and Dicke decided:

$$G \approx \phi^{-1} \quad (2.4)$$

because $\frac{m}{r}$ is a solution of a scalar wave equation where m relates to the point source. Here, ϕ represents the famed scalar field of the Brans-Dicke theory in which all of the universe's matter is used as the source [5].

With the conclusion that the gravitational constant G is inversely proportional to a scalar field, Brans-Dicke concluded that the proper theory of gravitation would be a scalar-tensor theory instead of the tensor theory proposed by Einstein.

2.3.3 The Action Principle and Field Equations

The Brans-Dicke action principle contains most of the intuitive ideas about their theory [5]:

$$A = \frac{c^3}{16\pi} \int_V (\phi R + \omega \phi^{-1} \phi^k \phi_k) \sqrt{-g} d^4x + A_{matter} \quad (2.5)$$

This equation pertains to a region of spacetime V . ϕ takes the place of the usual gravitational constant, G^{-1} , ω is a coupling constant, and A_{matter} contains the contributions from ordinary matter, as represented by T^{ik} . In addition, this action principle is key to attaining the field equations for the Brans-Dicke theory. As Narlikar explains, small changes of g^{ik} varies A and leads to the actual field equations, which are as follows [5]:

$$R_{ik} - \frac{1}{2}g_{ik}R = -\frac{8\pi}{c^4\phi}T_{ik} - \frac{\omega}{\phi^2}(\phi_i\phi_k - \frac{1}{2}g_{ik}\phi^l\phi_l) - \frac{1}{\phi}\phi_{ik} - g_{ik}\square\phi \quad (2.6)$$

where \square is the wave operator and ϕ_i is the covariant derivative of the scalar field. All of the terms in Eq. (2.6) beyond ordinary general relativity (see Eq. (2.1)) have to do with the fact that $G \sim \frac{1}{\phi}$ is now itself a variable, so from the chain rule of ordinary calculus, its derivatives must also be included in addition to the derivatives of g_{ik} when varying the action. Thus Eq. (2.6) shows that the curvature of space and time (the lefthand side) arises from two kinds of contributions in the Brans-Dicke theory: the distribution of ordinary matter and energy (as contained in T_{ik} , just as in ordinary general relativity), plus the behavior of the changing strength of gravity itself (arising from $G \sim \frac{1}{\phi}$).

$\square\phi$ can also be solved in order to get a complete solution. Varying the action with respect to ϕ leads to its own wave equation:

$$\square\phi = \frac{8\pi}{(2\omega + 3)c^4}T \quad (2.7)$$

where T is the trace of T_k^i .

As can be seen from this equation, the scalar and tensor components of the theory are mixed within the field equations. In these equations, Brans-Dicke realized that as $\omega \rightarrow \infty$, their solutions approach those predicted by general relativity. In other words, as this value increases, it costs more and more energy for ϕ to vary from place to place; variations in ϕ just become less and less dominant as ω increases, so that for large ω , ϕ behaves more or less like a constant. Therefore, by changing the value of ω , Brans and Dicke were able to bring their predictions very close to those of Einstein's.

In the following section, I will look at how experiments in the last several decades helped

distinguish the two theories and confirm the validity of general relativity.

2.4 Experimental Evidence

Results from recent experiments have helped conclude that the Brans-Dicke predictions, while quite close to those of Einstein, do not fit with these results. On the other hand, these same experiments have confirmed the predictions of general relativity. However, in 1966, the first experiment to validate the Brans-Dicke predictions was performed. With a specific value for ω , the Brans-Dicke theory accurately predicted the contribution to Mercury's perihelion advance due to the flattening of the sun. This was tested in what is now called the Dicke-Goldenberg solar oblateness results [3].

The previous results helped make the Brans-Dicke theory popular. In fact, for the next several years, many physicists were unclear about whether general relativity or Brans-Dicke's theory would be validated with upcoming experiments. Clifford Will writes amusingly of a saying in Kip Thorne's research group at Caltech [3]:

On Monday, Wednesday, and Friday, we believe in general relativity; on Tuesday, Thursday, and Saturday, we believe in Brans-Dicke theory (on Sunday, we go to the beach).

By the early 1970s, more accurate experiments began coming in that confirmed Einstein's general relativity more and more. For example, radio-wave light deflection experiments agreed with Einstein's predictions to 3% in 1972 while results in 1979 confirmed relativity predictions to 0.1 % [3]. In addition, all of these experiments were pushing the Brans-Dicke theory further away from feasibility, by putting more stringent bounds on the values of ω needed to match observations. Rather than ω being of order 1, as Brans and Dicke had suggested might be plausible, by 1979 observations limited $\omega \geq 500$. A theorist named Kenneth Nordtvedt concluded that the Brans-Dicke theory resulted in a breakdown of the equivalence principle in the presence of massive self-gravitating objects [3]. In 1976, experimental evidence showed that the equivalence principle did not break down as predicted, and therefore Einstein's general relativity was further confirmed.

2.5 Conclusions

Although experimental results have shown the validity of Einstein's general relativity over Brans-Dicke's alternative theory of gravitation, their theory has had a large impact on the physics community. It became one of the most popular, if not the most popular, of all the alternative theories to general relativity that have been proposed over the years. In addition, the direct consequences to physics because of this theory have been quite useful.

First, the Brans-Dicke theory helped to popularize general relativity, in a sense. Einstein's theory was ignored for a good portion of the early 20th century because it appeared to be experimentally infeasible. Lacking the proper technology and experiments, scientists during the early and mid-20th century focused on particle physics and other such increasingly popular fields of physics. However, alternative theories of gravity, such as the Brans-Dicke theory, resulted in a debate that sparked the curiosity of many physicists. In effect, in an attempt to confirm or disprove Einstein's famous theory, these physicists began to focus on it and develop new physics from its predictions. In recent years, general relativity has become of serious importance for many aspects of physics, including cosmology, particle physics, and attempts to unify gravity with the other forces. In addition, major technological advancements can be credited to the understanding of general relativity, including GPS systems. Therefore, while the Brans-Dicke theory itself may have been disproved through experiment, these experiments helped popularize a once ignored theory of general relativity that has had important consequences over time.

In addition, not only were physicists inspired to create experiments to test general relativity and these alternative theories, but the accuracy of experiments was significantly increased. Since the Brans-Dicke theory came up with predictions for certain events that were extremely close to Einstein's predictions, very accurate experiments were needed to separate the two theories. In the end, the technology was improved and new experiments were created that could differentiate between these two theories. Therefore, while helping to popularize the very theory they were offering an alternative to, the Brans-Dicke theory also played an integral role in motivating higher technology that could provide more accurate results.

Chapter 3

The Higgs Mechanism and Spontaneous Symmetry Breaking

While Brans and Dicke were forming their alternative theory to general relativity in 1961, Peter Higgs was contemplating a subtly similar idea of how elementary particles acquire mass. His ideas, called the Higgs mechanism, are currently included in the Standard Model. Although experimentalists have yet to find the Higgs boson, which is fundamental to his theory, the Higgs mechanism is generally accepted as the most valid theory explaining mass for elementary particles. While the Higgs' theory preceded the Standard Model, its very inclusion within this model is telling of the importance relegated to this theory. In this chapter, I will discuss the Higgs mechanism, including the Higgs field, Higgs bosons, and spontaneous symmetry breaking. Then, I will give a mathematical example of the Higgs mechanism and conclude with the mechanism's relevance to the Standard Model and current experimental attempts to verify the theory.

3.1 The Higgs Mechanism

Since Higgs published his ideas on particle mass creation in 1964, the Higgs mechanism has been the simplest and most well-accepted theory on this topic. Without this mechanism, the Standard Model would be incomplete because there would be no mention on how the fundamental particles included within the model come to be massive. Since mass is one of the important distinctive characteristics of most particles and so crucial in physics, a

proper theory of how particles gain mass is necessary for filling this otherwise large gap of understanding. In fact, major experimental efforts are currently underway to attempt a verification of Higg's theory.

Important similarities exist between the Brans-Dicke theory of gravity and the Higgs mechanism. The motivation behind both theories was to understand the origin of mass. In addition, both theories invented a new scalar field, ϕ , in order to explain how particles acquire mass. The Brans-Dicke scalar field, discussed in chapter 2, led to their scalar-tensor theory of gravitation. Similarly, the Higgs field is a scalar field in which particles acquire mass as they travel through it (the Higgs field is further discussed in section 3.1.3). Therefore, both the Brans-Dicke and the Higgs theories demonstrate how particles acquire mass from interactions with a new scalar field. Their astonishing similarities took years to connect, but have had a large impact on the physics community.

3.1.1 Overview

One of the most striking differences that has been explained by the Higgs mechanism is the existence of mass for any particle in the universe. Theorists in the 1960s knew of no way for particles to have mass while respecting gauge invariance for local gauge theories, which are discussed in the next section. Therefore, a fundamental question arose about how any particle, whether a fermion or a boson, could have any mass at all while respecting local gauge symmetries. The Higgs mechanism, through the clever addition of a scalar field, worked around this problem.

While the above is a general problem the Higgs mechanism solves, a specific question frequently discussed regarding the mechanism is its explanation of the extraordinary mass difference between W and Z bosons compared to the photon. The W and Z bosons mediate the weak interaction, just as photons mediate the electromagnetic force and gluons mediate the strong force. All of these particles are bosons, which are elementary particles that have integer spin and do not follow the Pauli exclusion principle. However, the mass differences between these bosons are impressive. The photon is massless while the W and Z bosons have masses nearly 100 times that of a proton. Their masses are, respectively, $80.4 \frac{GeV}{c^2}$ and $91.2 \frac{GeV}{c^2}$ [6]. As proposed by the electroweak theory, the electromagnetic and weak forces are unified at an energy around 100 GeV [6]. In proper physics terms, we can say that the

two forces arise from a common symmetry. Why, then, do the carrier particles for each of these forces have such drastically different masses? This Higgs mechanism is effective in answering this question, as we will see in later sections of this chapter.

3.1.2 Gauge Invariance

Before a general discussion of the Higgs field and boson, a brief discussion of gauge theories is important. In the theories that have thus far unified the weak, strong, and electromagnetic forces, such as the electroweak and quantum chromodynamics theories, the Lagrangians of the mediating bosons are invariant under gauge transformations. Thus, the photon, gluon, W and Z bosons are all gauge bosons. Such gauge invariance is an example of the symmetry that is essential within these quantum gauge field theories. Maintaining this gauge invariance is a very important aspect of these theories. For this reason, physicists were having trouble adding mass to particles: by doing so, gauge invariance was being broken. The necessity to maintain invariant Lagrangians under gauge transformations was bypassed by Higgs. In his mechanism, the Lagrangian itself remains invariant while its solutions do not necessarily appear to display these symmetries.

The unitary groups, containing the transformations that leave specific parts of the theories unchanged, are written as $SU(3) \times SU(2) \times U(1)$ for the three forces mentioned above. $SU(3)$ represents the quantum chromodynamics theory relating to the strong force. However, the $SU(2) \times U(1)$ cannot be easily split into relating to the weak and electromagnetic forces because of a complication that requires the Higgs mechanism to resolve. As a rule, the $SU(N)$ groups result in N^2-1 gauge bosons. Therefore, according to the simple prediction that $SU(2)$ relates to the weak force because $U(1)$ is known to relate to electromagnetism results in an assumption that three massless gauge bosons will be created to complement the one massless photon from the $U(1)$ interaction [7].

However, the gauge bosons for the weak force, the W and Z bosons, are known to be quite heavy. This mass is also evident in the action of the nuclear force, which is quite short-range. How can this dilemma be resolved so that the gauge invariant theory can stay consistent with quantum mechanics while the W and Z bosons have mass? To understand this, we must first introduce the Higgs field and boson. After this, a discussion of spontaneous symmetry breaking will explain more fully how the Higgs mechanism solves

this problem.

3.1.3 The Higgs Field

According to the theory, the Higgs field is a spin-zero scalar field that fills the universe. As particles travel through the field, they interact with it and gain mass in the process. The amount of mass acquired depends on the strength of the interaction. For example, particles that interact strongly with the Higgs field will be more massive than those that interact with it weakly. In addition, particles that are massless are those that do not interact at all with the field, such as photons and gluons.

Qualitatively, the Higgs mechanism states that as a particle moves through the Higgs field, the field in that region is affected and clusters around the particle. This clustering causes the particle to have mass. An alternative way of understanding this clustering is through the ‘drag’ effect. Particles that interact with the Higgs field are slowed so they cannot move at the speed of light, which can be considered their natural speed. This ‘drag’ effect makes the particles seem heavier, and thus more massive. On the other hand, particles like photons that do not interact with the field are able to move at the speed of light without this slowing effect. Of course, this is just another way to conceptualize the idea of particles traveling through this Higgs field.

A useful analogy about the Higgs mechanism was stated by British physicist David Miller in 1993 as follows [8]:

Imagine a cocktail party of political party workers who are uniformly distributed across the floor, all talking to their nearest neighbors. The ex-Prime Minister enters and crosses the room. All of the workers in her neighborhood are strongly attracted to her and cluster round her. As she moves she attracts the people she comes close to, while the ones she has left return to their even spacing. Because of the knot of people always clustered around her she acquires a greater mass than normal, that is she has more momentum for the same speed of movement across the room. Once moving she is hard to stop, and once stopped she is harder to get moving again because the clustering process has to be restarted. In three dimensions, and with the complications of relativity, this is the Higgs mechanism. In order to give particles mass, a

background field is invented which becomes locally distorted whenever a particle moves through it. The distortion - the clustering of the field around the particle - generates the particle's mass.

Another interesting aspect of the Higgs field is that it can exist within a vacuum. While most fields go to zero in a vacuum because zero is their lowest energy state, the Higgs field is actually at its lowest energy at a uniform value greater than zero. Therefore, this field can be thought of as a background presence that is always turned on within the universe.

3.1.4 Higgs Bosons

The Higgs boson is proposed to be a spin-zero, chargeless particle. In fact, the only distinct feature of this boson is that it has mass. Although current estimates are not certain of how massive the boson is, predictions suggest that it is a few hundred GeV [6]. Since quantum theory states that fields have associated particles, the assumption is that the Higgs boson complements the Higgs field. In theory, the Higgs bosons are contained within the field and act as the mediators of the interaction between particles and the field itself. Although this boson has not been discovered yet, it is thought to cause the spontaneous symmetry breaking that gives particles mass.

A continuation of Miller's analogy to Higgs bosons is as follows [8]:

Now consider a rumor passing through our room full of uniformly spread political workers. Those near the door hear of it first and cluster together to get the details, then they turn and move closer to their next neighbors who want to know about it too. A wave of clustering passes through the room. It may spread to all the corners or it may form a compact bunch which carries the news along a line of workers from the door to some dignitary at the other side of the room. Since the information is carried by clusters of people, and since it was clustering that gave extra mass to the ex-Prime Minister, then the rumor-carrying clusters also have mass. The Higgs boson is predicted to be just such a clustering in the Higgs field.

While the Higgs bosons are important as mediators, they have become even more popular in the physics community because they are the only current route to verifying the Higgs

mechanism. Experiments searching for the Higgs boson are discussed in section 3.2.2.

3.1.5 Spontaneous Symmetry Breaking

The most important consequence of the Higgs mechanism is the concept of spontaneous symmetry breaking. While this idea previously existed in physics, Higgs effectively incorporated it into his theory to solve previously unanswered questions. Spontaneous symmetry breaking explains how the electromagnetic and weak forces separated from their previously common symmetry to become so distinct. In other words, this part of the Higgs mechanism describes how the W and Z bosons became massive while the photon remained massless after the electroweak force was broken.

This spontaneous symmetry breaking occurred because particle energies decreased significantly after the early universe began to cool. Physicists believe that at high enough energies, all of the current four forces were unified into one. As the universe began to cool, gravity was the first to distinguish itself into a new force. Later, as the universe cooled more and thus particle energies fell even further, the strong force came into existence. Finally, the remaining unification, called the electroweak force, was split into the electromagnetic and weak forces by spontaneous symmetry breaking.

One way to think of spontaneous symmetry breaking is as follows: The electroweak force arose from a common symmetry when the universe had an equilibrium thermal energy of about 100 GeV. However, just as a carefully balanced ball on a hill must choose a direction to fall once it loses perfect balance, the electromagnetic and weak forces were forced to separate and become distinguished when the energy became too low for them to maintain their common symmetry. While the ball is perfectly balanced on the hill, it has no clear direction in which to fall. However, once this balance is broken, this symmetry is broken as well and one direction is chosen. This direction is in no way more special than the others - its being chosen is arbitrary. Although this famous ball on a hill example is a simplified version of the spontaneous symmetry breaking discussed here, the analogy is still informative. The distinction between the W and Z bosons compared to the photon arises from this spontaneous symmetry breaking which occurred as the universe cooled. According to the Higgs mechanism, the Higgs bosons induce the spontaneous symmetry breaking in this situation.

Now, we can return to the dilemma posed by the gauge invariant theory discussion in section 3.1.2. The massless gauge bosons required for the electroweak theory to be consistent within quantum theory are, in a way, possible. Since the W and Z bosons clearly are massive, the Higgs mechanism allows for them to be massless gauge bosons that gain mass when interacting with the Higgs field. By doing so, the gauge invariant theory which requires massless bosons is valid while the appearance of mass is explained by the Higgs mechanism.

Therefore, the electroweak theory suggests that the SU(2)xU(1) gauge symmetry yields four gauge bosons. Three of these bosons acquire mass while the fourth does not. Therefore, U(1) is the only gauge symmetry that remains because the other three resulting bosons have become massive. In the end, we can write that the spontaneous symmetry breaking results in the SU(3)xSU(2)xU(1) symmetry being broken into a SU(3)xU(1) symmetry.

3.1.6 Mathematical Example

Now that the Higgs mechanism has been explained qualitatively, we can look at it mathematically as well. The following example is a sufficient demonstration of the Higgs mechanism.

Suppose we begin with a Lagrangian for a complex scalar field ϕ such that it is invariant under the global gauge transformation $\phi \rightarrow \phi' = U\phi$ where U is a constant. This Lagrangian can be written as [7]:

$$L = (\partial_\mu \phi)^*(\partial^\mu \phi) - \mu^2 \phi^* \phi - \lambda(\phi^* \phi)^2 \quad (3.1)$$

where $\phi = \frac{(\phi_1 + i\phi_2)}{\sqrt{2}}$

We can see that a possible value for U that upholds the global gauge invariance for the Lagrangian is:

$$\phi' = e^{i\chi} \phi \quad (3.2)$$

where χ is a constant.

However, in this discussion, we are interested in making the Lagrangian invariant under a local gauge transformation, $U(x) = e^{i\chi(x)}$. To do this, a new massless vector field A_μ must be introduced. Otherwise, the covariance of the derivative and field terms will not match (Kaiser). In a similar example, Kaiser demonstrates this as follows [9]:

$$\partial_\mu \phi' \rightarrow \partial_\mu(U(x)\phi) = U\partial_\mu\phi + \phi\partial_\mu(U(x)) \neq U(\partial_\mu\phi) \quad (3.3)$$

Our goal here is to construct covariant derivatives that allow L to be gauge invariant. At the end, we will be able to test whether our derivatives do, indeed, allow for L to maintain this invariance. It is the consequences of these covariant derivatives that allow the Higgs mechanism to work, as will be seen later.

We will require that the new field, A_μ , transforms as follows [7]:

$$A_\mu \rightarrow A_\mu' = A_\mu + \frac{1}{g}\partial_\mu\chi(x) \quad (3.4)$$

where g is a coupling constant and $\chi(x)$ is a transformation parameter.

Therefore, we can now construct our covariant derivatives which which permit L to remain gauge invariant [7]:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + igA_\mu \quad (3.5)$$

From the above equation and the definition of ϕ , we can state that that the following condition on $(D_\mu\phi)'$ must hold [9]:

$$(D_\mu\phi)' = \left(\partial_\mu + ig \left[A_\mu + \frac{1}{g}\partial_\mu\chi \right] \right) (e^{-i\chi(x)}\phi) \quad (3.6)$$

Manually performing the above derivatives and simplifying the answer yields:

$$(D_\mu\phi)' = e^{-i\chi}D_\mu\phi \quad (3.7)$$

The above condition is necessary for creating the appropriate covariant derivatives in this example. Then, making the above substitutions to ensure that the Lagrangian is invariant under local gauge transformations, L becomes:

$$L = (D_\mu\phi)^*(D^\mu\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \mu^2\phi^*\phi - \lambda(\phi^*\phi)^2 \quad (3.8)$$

where the $\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ is a kinetic energy term of the vector field and the last two terms are a potential for ϕ .

Now, let's discuss these last two terms from the above equation. When $\mu^2 < 0$, we see that this is a double-well potential. A class of degenerate vacuum states exists, similar to

the ball on the hill explained qualitatively earlier.

We can parameterize the complex scalar field, ϕ , in terms of two real scalar fields, $\eta(x)$ and $\rho(x)$:

$$\phi = \frac{1}{\sqrt{2}}(v + \eta(x))e^{i\rho(x)/v} \quad (3.9)$$

where v is a constant.

Taking into account that we are only interested in small fluctuations around the vacuum state ($\phi = v$), we see that:

$$\phi \rightarrow \frac{1}{\sqrt{2}}(v + \eta + i\rho) \quad (3.10)$$

Now, we can substitute the above equation into our definition of covariant derivatives to get:

$$(D_\mu\phi)(D^\mu\phi)^* = \frac{1}{2} [(\partial_\mu + igA_\mu)(v + \eta + i\rho)(\partial^\mu - igA^\mu)(v + \eta - i\rho)] \quad (3.11)$$

$$= \frac{1}{2} [(\partial_\mu\eta)(\partial^\mu\eta) + (\partial_\mu\rho)(\partial^\mu\rho) + g^2v^2A_\mu A^\mu + 2gvA_\mu(\partial^\mu\rho)] \quad (3.12)$$

When $\mu^2 = -v^2 < 0$, a further substitution of the above equation into the Lagrangian shows:

$$L = \frac{1}{2} [(\partial_\mu\eta)(\partial^\mu\eta) - 2|\mu|^2\eta^2] + \frac{1}{2}(\partial_\mu\rho)(\partial^\mu\rho) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g^2v^2}{2}A_\mu A^\mu + gvA_\mu(\partial^\mu\rho) \quad (3.13)$$

The above Lagrangian demonstrates the core of spontaneous symmetry breaking and the Higgs mechanism. By looking at the terms, we see that the massless fields $\eta(x)$ and $\rho(x)$ we introduced earlier are no longer the same. In fact, the η field has picked up a mass, seen by the term $2|\mu|^2$. Although the same is not true for the ρ field, the last term of the equation indicates that this massless field has become coupled with the gauge field we initially introduced, A_μ .

Looking at the last two terms in the above Lagrangian, we can compare even further to our original equations. We see that these terms are U(1) gauge transformations on A_μ ,

which is:

$$A_\mu \rightarrow A'_\mu = A_\mu + \frac{1}{gv} \partial_\mu \rho \quad (3.14)$$

Remember, this is equatable to Equation 3.4. Finally, since we have already determined that the Lagrangian itself is invariant under local U(1) transformations, we can further reduce our Lagrangian as follows:

$$L = \frac{1}{2} [(\partial_\mu \eta)(\partial^\mu \eta) - 2|\mu|^2 \eta^2] - \frac{1}{2} \left[\frac{F'_{\mu\nu} F'^{\mu\nu}}{2} + g^2 v^2 A'_\mu A'^\mu \right] + \text{interactions} \quad (3.15)$$

This last Lagrangian shows the complete beauty of the mechanism. We see that the gauge field A_μ has acquired mass in the form of $g^2 v^2$ while the ρ field has disappeared altogether.

Thus, the degrees of freedom in the system have been conserved. We began with two massless scalar fields and one massless vector field. The scalar fields each have one degree of freedom while the vector field has two. Therefore, we started with a total of four degrees of freedom in our system. In the end, we have one scalar field and one massive vector field remaining. Thus, we end up with four degrees of freedom; one from the scalar and three from the massive vector field.

3.2 The Higgs Particle Today

Nearly forty years have passed since Higgs proposed his theory of how particles acquire mass in the universe. During this time, the Higgs mechanism has become quite popular. Although the Standard Model did not even exist when Higgs was formulating his theory, the Higgs mechanism has been included in this model as the only valid theory of mass creation. Therefore, this theory has become fundamental to particle physics although it has not yet been effectively tested. However, experimental physicists are working hard right now to fix this last issue. Major experiments are being conducted to search for the Higgs boson, which is the most feasible way of verifying the Higgs mechanism. In this section, I will introduce the Standard Model and discuss recent experiments that have played a role in the Higgs discourse. Experimental physicists are working hard right now to fix this last issue. Major

experiments are being conducted to search for the Higgs boson, which is the most feasible way of verifying the Higgs mechanism. In this section, I will introduce the Standard Model and discuss recent experiments that have played a role in the Higgs discourse.

3.2.1 The Standard Model

The Standard Model, compiled in the 1970s by combining theoretical work in particle physics with experimental results, is the theory of fundamental particles and their interactions. Gravity is not included in this model since it is the only force that has not been unified with the other forces yet. On the other hand, the weak, strong, and electromagnetic forces are the foundations of this model. In the end, the Standard Model consists entirely of the three currently unified forces and information on the fermions and bosons that are essential for the creation of matter and its interactions. The only other component, then, is the feature that leads to mass creation. It is here that the Higgs Mechanism comes into the Standard Model. While the Standard Model is believed to eventually fail in describing some interactions, it is sufficient and quite accurate on the scale at which the current three forces are relevant. Efforts, such as string theory, are currently underway to create a Theory of Everything which includes gravity. Historically, particle physics has been most concerned with only the other three forces, while gravity is only now becoming an important feature of particle theories. The unification of those three forces is called the Grand Unified Theory. The essential notion is that although cooling of the universe has resulted in a splitting of the forces, at one point in the early universe these forces were contained within a common symmetry. In other words, at high enough energies, all of the forces are unified into one force.

The current model states that electromagnetism and the weak force merge at energies on the order of 100 GeV, forming the electroweak force. On the other hand, while current estimates of the energy needed to unify the electroweak and strong forces are not well established, a proposed figure is 10^{15} GeV [6]. Unifying gravity with these three would require energy above this latter figure. Current experiments can only reach a few GeV, and thus are so far unable to even access energies close to these latter two predictions. As mentioned, while much of this research was done in particle physics, trying to unify gravity and these other reactions has increased the communication between particle physicists and

cosmologists.

Therefore, while the Standard Model may suffer from its incompleteness if all four forces are unified, the Higgs mechanism will continue to be an important player in the new theory. The reason for this is simple - the mechanism is still the simplest and most well-accepted theory of mass creation. The only feasible way for the Higgs mechanism to become unpopular in the near future appears to be if current experiments are unable to verify the theory or discover evidence that contradicts it. In the following section, I discuss the current experimental research being conducted on this topic.

3.2.2 Experimental Results

Since Higgs proposed his theory in the mid-60s, experimental physicists are coming closer and closer to being able to test it. While the Higgs field itself is difficult to discover experimentally, if not impossible, the Higgs boson is quite feasible. In fact, the last several years have seen major advances in searching for the Higgs boson.

Researchers at the Large Electron-Positron (LEP) Accelerator at CERN in 2000 believed they had caught site of the Higgs boson at around 115 GeV, but the statistical data was inconclusive [10]. While LEP was shut down, the current hope is that the Large Hadron Collider (LHC) at CERN, which is currently being built and will begin operation in 2007, will be able to detect the Higgs boson [10]. The LHC should be able to search for the Higgs boson at energies past 211 GeV, which is the top estimate for its mass.

During this gap of seven years between CERN operations, physicists at Fermilab's Tevatron particle accelerator are currently trying to find the Higgs boson [10]. However, the prospect of their success is low due to the age of the accelerator and the equipment necessary to conduct the experiments.

Discovering the Higgs boson would verify the Higgs mechanism. In doing so, a very large portion of particle physics would be better understood. For this reason, physicists are anxiously awaiting results from the costly particle accelerators.

3.3 Conclusions

Over the last forty years, the Higgs mechanism has been generally accepted by the physics community as the simplest theory explaining how particles become massive. While other

theories have been proposed over the years, the Higgs mechanism is the only one to have become part of the Standard Model. Not only does this mechanism explain how particles acquire mass, but it also works well with quantum theory and the need to maintain the key properties of gauge theories for the main forces within the Standard Model.

While the Higgs field and Higgs boson are key players in spontaneous symmetry breaking according to the theory, confirmation of these claims will only be provided through experimental results. However, since the search for the Higgs boson is a top priority within the physics community at the moment, lack of experiments is not an issue. Perhaps within the next decade, through experiments at the new LHC accelerator, the Higgs boson will be discovered. Otherwise, its lack of discovery may lead to further, more complicated theories on the topic of how particles acquire mass in the universe.

Chapter 4

The Makings of the Inner Space - Outer Space Connection

Even though current advances in physics, such as string theory, demonstrate an intimate connection between cosmology and particle physics, this trend is relatively new. In fact, during the time of the Brans-Dicke theory of gravitation and the Higgs mechanism in the 1960s, the two fields were quite isolated. Although both of these theories have numerous similarities and motivations, physicists did not even realize this closeness for many years. Approximately forty years have passed since Brans, Dicke, and Higgs formulated their theories about mass - and it has taken nearly that long for the two fields to form a strong connection. However, the bridge between these two important branches of physics has been slowly built over the last few decades. Efforts for grand unification of forces involving gravity have pushed this connection to the forefront of physics.

In the next section, I will use the two theories discussed so far to demonstrate the lack of dialogue between cosmology and particle physics during the early years after the theories' formulation. In the following section, I will look at categorization of physics publications over the last forty years to generalize the claims from the previous section.

4.1 Brans-Dicke and the Higgs Mechanism: 1961-1981

Following the use of the Brans-Dicke theory of gravitation and the Higgs mechanism over the years is very telling of the way cosmology and particle physics have changed during that time. While these two theories are clearly not the only components of their fields, their impact on physics has been significant. In addition, their close parallels are well-suited for a historical look at why these theories were kept so separated for so many years. As mentioned in previous chapters, one of the most interesting aspects of the Brans-Dicke theory of gravitation and the Higgs mechanism is their similarities. As demonstrated in chapters 2 and 3, both of these theories attempt to explain how particles acquire mass in the universe. In addition, both apply nearly the same mathematical techniques of creating scalar fields that are coupled to the mass in the universe. In a way, the theories are so similar they can be viewed as different versions of the same concept.

Not surprisingly, these two theories became quite popular in their fields. As mentioned in chapter 2, the Brans-Dicke theory was given credence by some experimental evidence and physicists who believed that it matched the spirit of general relativity while maintaining Mach's principle. Although it took a few years for the theory to pick up steam, by the late 1960s, several journal articles were citing the original 1961 Brans-Dicke paper. By 1981, their paper had been cited 538 times. Although the theory's popularity decreased by the late 1970s because of the experimental evidence against it, the Brans-Dicke article was still often cited in cosmology papers. Figure 4-1 shows the increase in total citations over time. Similarly, the three papers published by Higgs between 1964 and 1966 also became quite popular in their own field of particle physics. The number of journal articles citing these papers spiked in the early 1970s, as seen in Figure 4-2. The Higgs mechanism continued to be popular even after the 1970s. By 1981, the three Higgs papers had been cited a total of 545 times.

From this information about citations, we can make two conclusions about the Brans-Dicke and Higgs theories. First, both of these theories were popular during key periods during the 1960s to 1980s. This is important because otherwise, making conclusions about trends in cosmology and particle physics based on obscure theories is imprudent. However, historical record demonstrates that both the Brans-Dicke theory and the Higgs mechanism

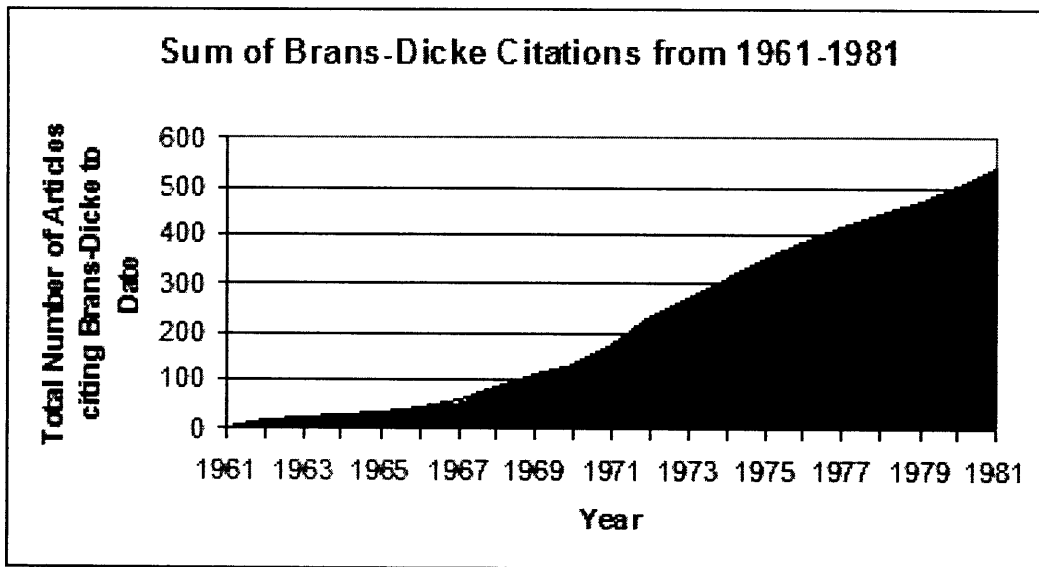


Figure 4-1: This figure shows the accumulation of papers citing the Brans-Dicke article from 1961 to a given year. In other words, the number of articles corresponding to 1975 on this graph indicates the number of articles that have cited the Brans-Dicke paper from 1961-1975.

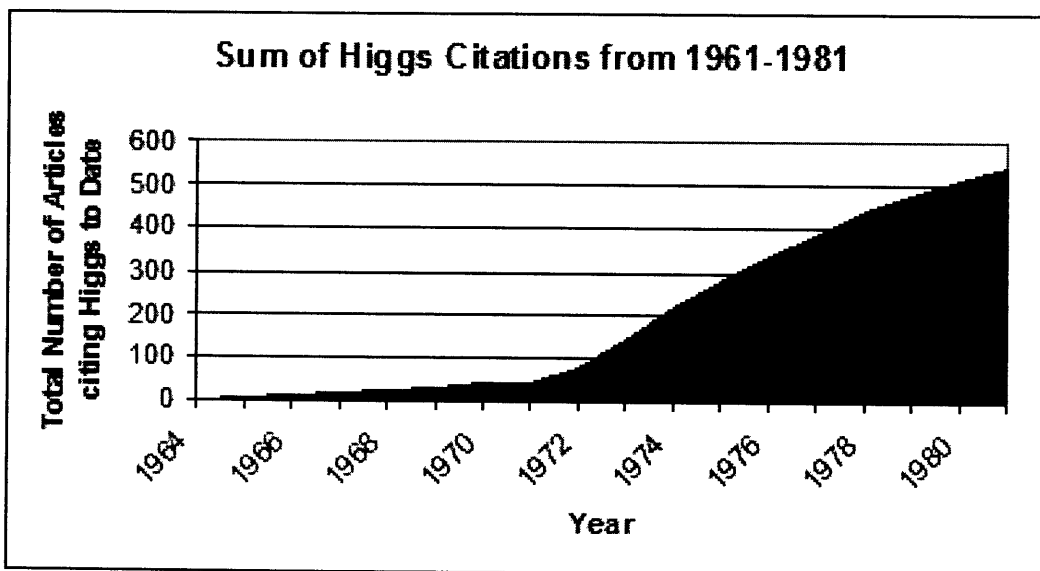


Figure 4-2: This figure, relating to the number of papers citing one or more of the three Higgs papers, is similar to Figure 4-1. Each year shows the cumulative number of articles that have cited the Higgs papers since 1961.

were far from obscure. Second, these theories were in relative proximity in their popularity. In a period of twenty years, both theories were cited nearly the same number of times within their own fields. Therefore, these theories serve as decent models to look at how cosmology and particle physics have interacted over the years.

Looking at the number of times physicists cited both the original Brans-Dicke paper and one or more of the Higgs papers from 1961 to 1981 is an interesting study. In this entire period of 20 years and 1083 papers ¹, only six journal articles reference both Higgs and Brans-Dicke. The first of these double citations occurred in 1972, but the rest are mostly from 1975 onward. In fact, out of a total of 990 authors who wrote these journal articles, only 21 of them ever referenced both Brans-Dicke and Higgs, even in separate articles during this twenty year period. This huge gap, especially with the understanding we now have about the similarities between these two theories, demonstrates the low level of communication between the cosmologists and particle physicists at that time.

While the comparison between the articles referencing the Brans-Dicke and Higgs papers offers a cursory glance at the situation between cosmology and particle physics during the second half of the twentieth century, an even deeper look into the relationship between these fields is helpful. The next section provides a more compact look at how these two fields have changed over time with regards to each other.

4.2 Overall Connection Between Cosmology and Particle Physics

While the previous section uses the Brans-Dicke and Higgs theories to demonstrate the deep communication divide between cosmology and particle physics in the 1960s and 1970s, this difference is even more obvious by looking at the categorization of papers published in these fields between the period of 1961 to 1991. For example, a look at the subject titles that articles categorized under the term ‘cosmology’ are placed under in the Physics Abstracts is an effective way of measuring this change in the two fields. The Physics Abstracts, a monthly publication organized by an international team of physicists, publishes abstracts of every physics paper in several hundred physics journals from around the world. In

¹This number is the number of papers that have cited Brans-Dicke and Higgs during this period: 538 and 545, respectively.

addition to labeling articles by their discipline, each one is also assigned a single sub-category. Therefore, by examining what sub-category articles listed under the discipline of ‘cosmology’ are in, we can trace the integration of particle physics into cosmology. In this section, I will look at how this data demonstrates both the slowness of bringing these two fields together as well as how a bridge between them has been built over the last few decades.

4.2.1 Particle Physics within Cosmology

First, the field of cosmology itself has grown over the 30 year frame between 1961 and 1991. For various reasons, cosmologists have been better accepted into the physics community during this period. In addition, advances in technology have increased the number of cosmological experiments that are possible, thus allowing for verification of once purely theoretical work. A preliminary look at the data from the Physics Abstracts demonstrates this dramatic rise of cosmology as a field of physics. In 1961, only 77 papers were published under the category of ‘cosmology’. Ten years later, this number increased to 223. In 1981, 491 papers were published under this category and finally, in 1991, the number rose to a total of 1129 papers. Clearly, this period of thirty years saw great growth in the field of cosmology, which was important in establishing it as a true branch of physics.

But how, then, has particle physics played into cosmology over these years? We can first examine this question by looking at the sub-categories under which the above papers were labeled. In other words, although all of the papers mentioned above were categorized under ‘cosmology’ in the index, each one was placed into a specific subject category depending on the type of paper. To look at how particle physics has entered into cosmology, we can look at how many papers listed under ‘cosmology’ were placed into subjects relating to nuclear and particle physics.

Upon performing the above analysis, a trend regarding the increase in communication between the two fields is evident. In 1961, only 3 of the 77 papers listed under cosmology were labeled as nuclear physics. Most of the other papers were in the category of astrophysics or relativity. Similarly, in 1971 the ratio was quite dismal as well - only 7 of 233 papers came under the category of Elementary Particles. However, by 1981 the number of papers relating to particle physics and categorized as cosmology were greatly increasing. In that

year, 41 papers out of 491 fit into this group. This is nearly a 300% increase compared to the numbers in 1971 - quite a dramatic shift for a decade. As we saw in section 4.1, most of the co-citations for the Brans-Dicke and Higgs papers occurred between 1975 and 1981. Therefore, these previous results are representative of the time when the proportion of joint particle physics and cosmology papers was itself leaping forward. In 1991, 72 of the 1129 papers fell into the particle physics categories. Table 4.1 shows the above information more concretely.

# of Articles	1961	1971	1981	1991
Total	77	223	491	1129
Particle Physics	3	7	41	72
Astrophysics	68	206	429	1005
Miscellaneous	6	10	21	52

Table 4.1: This table shows the numbers of articles published during the stated year in the categories listed. Particle physics includes elementary particles as well as nuclear physics while astrophysics includes radioastronomy and gravitation.

Although astrophysics is by far the main subject articles categorized under cosmology fall into for each of these four years, the number of articles that fit both cosmology and particle physics are clearly increasing. So, while more papers continue to be published in cosmology as this field grows, we are also seeing an increase in the number of papers that are merging concepts from both cosmology and particle physics. While not huge, this latter figure demonstrates a growing connection between the two fields. A complete listing of the subject counts for each year can be found in Appendix A.

4.2.2 The Global Links between Cosmology and Particle Physics

Not only is the information from the previous section telling about the relationship between cosmology and particle physics from 1961 to 1991, but a look at the countries associated with the few articles relating the two fields is also useful. In order to do such an analysis, we can look at the countries of the authors' institutions. By doing so, we can see how the connection between the two fields has spread throughout the world. This section provides

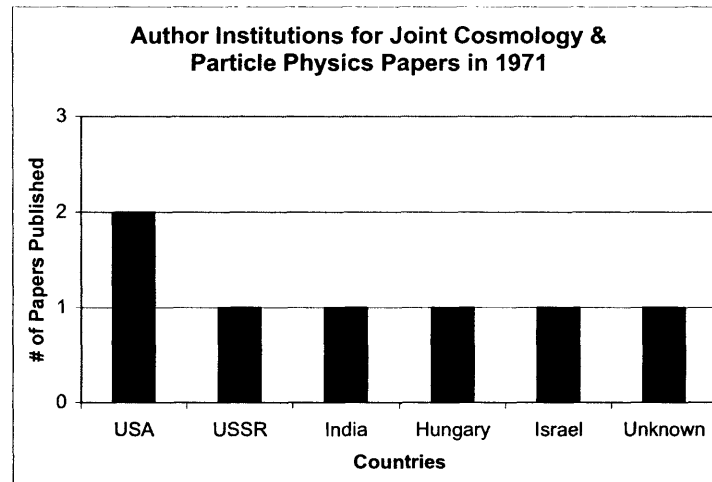


Figure 4-3: This graph shows the countries of the institutions in which physicists wrote joint cosmology and particle physics articles published in 1971.

such an analysis based on the articles connecting particle physics and cosmology mentioned in the previous section.

So, the first question is to understand who has been working on joint topics of particle physics and cosmology, and when this work was published. For this discussion, I will only refer to the articles mentioned in the previous section which related to both particle physics and cosmology (i.e. the three articles from 1961, the 7 from 1971, and so on). All three relevant articles from 1961 were published in the USSR by Russian physicists. By 1971, the countries of the authors' institutions were already more diverse - only 1 paper was from the USSR; the rest were from India, Hungary, USA, Israel, and Great Britain. A similar change was seen a decade later; at least nine countries represented the authors' institutions in 1981. The largest increase, however, is seen in the 1991 data. Here, authors' institutions ranged over nineteen different countries. This data for 1971, 1981, and 1991 is detailed in Figures 4-3, 4-4, and 4-5, respectively. 1961 is not included because, as mentioned above, the only three papers published were from authors and journals in the USSR.

The above data suggests that the work connecting particle physics to cosmology was

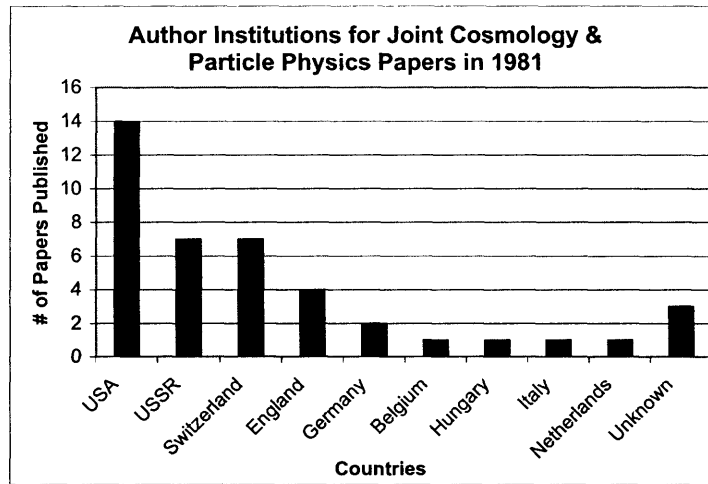


Figure 4-4: This graph shows the countries of the institutions in which physicists wrote joint cosmology and particle physics articles published in 1981.

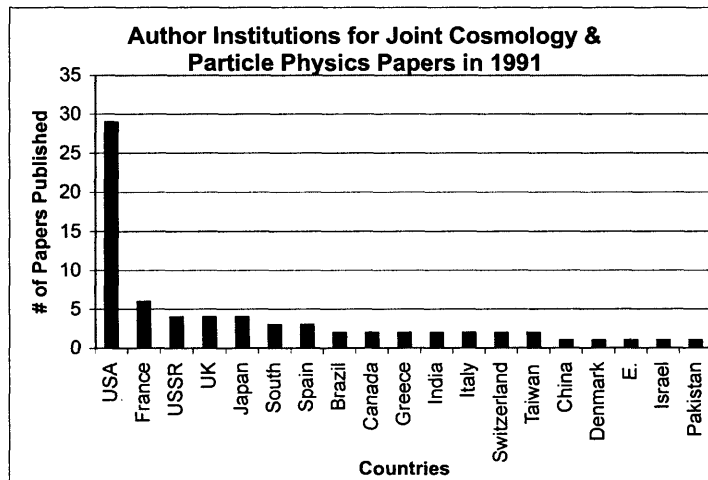


Figure 4-5: This graph shows the countries of the institutions in which physicists wrote joint cosmology and particle physics articles published in 1991.

being done in various institutions around the world by the later decades of this analysis. Although in 1961 the USSR appeared to be dominant in bringing together particle physics and cosmology, by as early as the next decade, the institutions in which this work was being done had expanded globally.

While perhaps less significant, another interesting measure of the global expansion of joint particle physics and cosmology research is tracing the number of countries in which journals containing such articles were published. Again, in 1961 the three papers of interest were published in the USSR. 1971 saw a slight increase - journals within the USSR, Great Britain, USA, and India all published articles related to both cosmology and particle physics. Then, by 1981 six countries total were publishing such articles. However, the sharpest rise was evident in the years between 1981 and 1991, because by 1991, a total of ten countries contained journals with these joint articles. Although the author institution data is more significant because it represents the locations of where the work itself was being done, the journal data provides more evidence that the joint cosmology and particle physics papers were increasing globally.

4.3 Conclusions

We can again ask the question: How did theorists in cosmology and particle physics overlook such dominant theories from the other field, such as the Higgs mechanism and the Brans-Dicke theory of gravitation? This question is especially pertinent since the two theories are so similar in motivation and method. Simply, we can conclude that the two fields were so isolated from each other during this period that physicists in neither field were aware of the other theories for quite some time. As the analysis shows, the fields of cosmology and particle physics were quite separated during the 1960s and even part of the 1970s. While the *theories* themselves got little attention from the other field, a broader generalization suggests that neither *field* got much attention from the other field during much of this time period. The bridge linking the two theories was very slow to develop, only really picking up during the 1980s and 1990s. In addition, by looking at the countries in which authors who are connecting the two fields work, we can see that this bridge is spreading across the globe and is no longer isolated to one country, as it was in 1961. Recent trends suggest that both fields interact much more heavily now than they did previously.

Chapter 5

Conclusions

As we have seen, the Brans-Dicke theory of gravitation, invented as an alternative to Einstein's general relativity, and the Higgs mechanism are very similar theories constructed within two very separated fields of physics at the time. Although both cosmology and particle physics are beginning to find common ground now, forty years ago when these theories were created there was nearly no communication between physicists in either category. Ironically, the theories were closer to each other than the physicists who invented them.

Both the Brans-Dicke theory and the Higgs mechanism have had a significant impact on physics. As discussed in chapter 2, the eventual failure of the Brans-Dicke theory of 1961 is nearly irrelevant compared to the positive impact the theory's existence had on cosmology. Not only did the theory spark interest in topics related to general relativity, but its closeness to the predictions of Einstein's theory encouraged improved experimental accuracy and designs. In the end, experiments resulting from this interest helped confirm predictions of general relativity. Although perhaps not the end goal desired by Brans and Dicke when they formulated their theory, their ideas helped advance physics in many ways. Similarly, the Higgs mechanism, explained in chapter 3, has played a large role in particle physics since its formulation in the mid-1960s. While independent and prior to the Standard Model, the theory's incorporation into this model demonstrates its significance in the field. In fact, the Higgs mechanism is still the only generally accepted theory of mass creation in particle physics. Unlike the Brans-Dicke theory, which has been sidelined in recent years, current experiments are still attempting to verify whether Higgs was correct or not.

The significance of these two theories is not only in what they have contributed to their

field, but in their closeness to each other as well. Considering that each theory is attempting to solve the same question of how particles acquire mass in the universe, it is reassuring that they are so similar. Despite the superficial differences because of the differing foundations the theories are based within (i.e. cosmology versus particle physics), the mathematics in the theories is alike in many ways. The introduction of a new scalar field that is coupled to the mass within the universe is the main feature of both theories. This common link is, perhaps, the most interesting and startling feature of their closeness. Making an analogy to how the four forces are believed to have arisen from a common symmetry, we can say that these two theories are so fundamentally similar that they too hold a common symmetry!

An explanation of how the similarities between these two theories went unnoticed for several years is found by looking at how the cosmologists and particle physicists communicated during that time period. As we have seen in chapter 4, plenty of evidence demonstrates that during the 1960s and even 1970s, there was hardly any overlap between cosmology and particle physics. This lack of association began to dissolve during the 1980s, and by the last decade of the twentieth century, the two fields had found similarities regarding some theories. The current trend has been toward further association because of the theoretical advances being made to establish a unified theory of all four fundamental forces.

In the end, the Brans-Dicke theory and the Higgs mechanism have contributed to the advances in physics made during the last century. Not only have they made an impact on their own fields, but in ways, they have been players in bringing the fields of cosmology and particle physics closer together. In the end, whether the Higgs mechanism is dismissed like the Brans-Dicke theory was eventually, the long-lasting impact both theories have had on physics and the physics community will be irreplaceable.

Appendix A

Subject Counts

This appendix includes the full subject listings for the papers described in section 4.2. The sub-category of the papers labeled as cosmology in the Physics Abstracts index are included here, along with a count how many papers were published under each such sub-category. This analysis was done for 1961, 1971, 1981, and 1991.

The number next to each subject listing indicates the number of papers published under this topic. Sub-categories themselves were split into further categories, which are indented in the following lists. Thus, using 1961 as an example: Mathematics is a main sub-category while Radioastronomy is a further category under the main sub-category of Astrophysics. Next to each main sub-category is a number in parentheses - this number is the sum of all the smaller categories within this sub-category. Again, using 1961, we see that 56 papers were published under the sub-category of Astrophysics while a further 7 were published under Radioastronomy. Therefore, 63 papers total can be included within the sub-category of Astrophysics. In addition, any sub-categories with no joint particle physics and cosmology articles have been italicized and have no numbers next to them. Please refer to chapter 4 for an analysis of this data.

A.1 1961 Subject Count

- Mathematics: 1 (1)
- Astrophysics: 56 (63)
 - Radioastronomy: 7

- Physics (10)
 - Gravitation - Relativity: 5
 - Mechanics of Gases:
 - * Shock Waves: 1
 - Plasma: 2
 - Electromagnetism Magnetohydrodynamics: 2
- Nuclear Physics (3)
 - Elementary Particles
 - * Photons: 1
 - * Neutrinos: 1
 - Nuclear Reactions Due to Neutrons: 1
- *Atomic and Molecular Physics*
- *Solid-State Physics*
- *Physical Chemistry*
- *Geophysics*
- *Biophysics - Physiological Physics*
- *Technique - Materials*

A.2 1971 Subject Count

- General: 1 (1)
- Mathematical Physics: (18)
 - Gravitation - Relativity: 16
 - Quantum Theory: 1
 - Statistical Physics: 1
- *Mechanics, Elasticity, Vibration, and Acoustics*
- Heat-Thermodynamics: 1 (1)
- *Electromagnetism*
- Electrodynamics and Particle Optics: 2 (2)
- *Quantum Electronics, Quantum Optics*
- *Optics*
- *Quantum Field Theory*

- Elementary Particles: 1 (7)
 - Elementary-particle theory: 1
 - Leptons: 1
 - * Neutrinos: 1
 - Hadrons
 - * Kaons: 1
 - Cosmic Rays: 2
- *Elementary Particle & Nuclear Measurement*
- *Nuclear Physics*
- *Atomic & Molecular Physics*
- Fluids: 1 (3)
 - Plasma: 1
 - Gaseous State: 1
- *Change of State*
- *Solid-State Structure & Mechanical Properties*
- *Solid-State Electrical & Magnetic Properties*
- *Solid-State Spectroscopy & Optical Properties*
- *Physical Chemistry*
- Geophysics: 1
- Astrophysics: 168 (190)
 - Galaxies: 16
 - Stars: 3
 - Radio Sources, X-Ray and Gamma Sources: 2
 - Solar System: 1
- *Biophysics*
- *Laboratory & Experimental Techniques*

A.3 1981 Subject Count

- General (67)
 - Communication, Education, History, and Philosophy: (15)
 - * Physics Literature and Publications
 - Conference Proceedings: 5
 - Monographs, and collections: 4
 - Textbooks for graduates and researchers: 2
 - * Educational Aids: 3
 - * Biographical, historical, and personal notes: 1
 - Classical and Quantum Physics; Mechanics and Fields: (2)
 - * Special Relativity: 1
 - * Classical Mechanics of Continuous Media: General Mathematical Aspects: 1
 - Relativity and Gravitation: (47)
 - * General Relativity: 27
 - * Gravitational Waves and Radiation: Theory: 2
 - * Continuous Media; electromagnetic and other mixed gravitational systems: 4
 - * Unified Field Theories and Other Theories of Gravitation: 6
 - * Quantum Theory of Gravitation: 7
 - * Experimental tests of general relativity and Observations of Gravitational Radiation: 1
 - Statistical Physics and Thermodynamics (2)
 - * Quantum Statistical Mechanics: 1
 - * Lattice Theory and Statistics; Ising Problems: 1
 - Measurement Science, General Lab Techniques, and Instrumentation systems: (1)
 - * Metrology
 - Units: 1
- The Physics of Elementary Particles and Fields (39)
 - General Theory of Fields and Particles: (11)
 - * Field Theories: 8
 - * Symmetry and Conservation Laws: 3
 - Specific theories and interaction models; particle systematics: (23)
 - * Unified and electromagnetic interaction theories
 - Experimental Tests of quantum electrodynamics: 1
 - Unified field theories and models: 18
 - * Composite Models of Particles: 3

- * Models of Strong Interactions:
 - Bootstrap models: 1
- Specific Reactions and phenomenology: (4)
 - * Neutrino Interactions: 1
 - * Electromagnetic processes and properties
 - Electromagnetic form factors; electric and magnetic moments: 2
 - * Hadron-Induced-High and Super-High-Energy Interactions, Energy $>10\text{GeV}$: 1
- Nuclear Physics (2)
 - Nuclear Reactions and Scattering: Specific Reactions: (2)
 - * Nucleon-induced reactions and scattering: 1
 - * Heavy-particle-induced reactions and scattering: 1
- *Atomic and Molecular Physics*
- *Classical Areas of Phenomenology*
- *Fluids, Plasmas, and Electric Discharges*
- *Condensed Matter: Structure, Thermal and Mechanical Properties*
- *Condensed matter: electronic structure, electrical, magnetic, and optical properties*
- Cross-disciplinary physics and related areas of science and technology (1)
 - Biophysics, medical physics, and biomedical engineering: (1)
 - * Other topics in biophysics, medical physics, and biomedical engineering: 1
- Geophysics, Astronomy, and Astrophysics (383)
 - Aeronomy and Space Physics (1)
 - * Cosmic Rays
 - Composition and energy spectra: 1
 - Fundamental Astronomy and Astrophysics, Instrumentation and Techniques and Astronomical Observations: (28)
 - * Fundamental Aspects of Astrophysics: 27
 - * Other topics in Astronomy and Astrophysics: 1
 - Stars: (12)
 - * Late Stages of Stellar Evolution: 5
 - Supernovae: 1
 - Neutron Stars: 2
 - Black Holes: 9
 - Stellar systems; galactic and extragalactic objects and systems; the universe: (342)

- * Stellar Clusters and Associations: 3
- * Interstellar Matter; and Nebulae: 1
- * The galaxy, extragalactic objects, and systems: 28
 - Groups, clusters, superclusters: 16
- * Other Objects and Background Radiations of Unknown Origins and Distances:
 - Discrete Radio Sources: 15
 - Quasars: 20
 - Background Radiation: 26
- * Cosmology: 233

A.4 1991 Subject Count

- General (125)
 - Communication, Education, History, and Philosophy: (41)
 - * Physics Literature and Publications
 - Publications of lectures: 1
 - Conference Proceedings: 32
 - Textbooks: 3
 - * Educational Aids: 2
 - * General Physics: 1
 - * History of Science: 1
 - * Philosophy of Science: 1
 - Classical and Quantum Physics; Mechanics and Fields: (7)
 - * Classical Mechanics of Continuous Media: General Mathematical Aspects
 - Mathematical Theory of Elasticity: 1
 - * Quantum Theory; Quantum Mechanics: 6
 - Relativity and Gravitation: (74)
 - * General Relativity: 21
 - * Gravitational Waves and Radiation: Theory: 3
 - * Continuous Media; electromagnetic and other mixed gravitational systems: 7
 - * Unified Field Theories and Other Theories of Gravitation: 20
 - * Quantum Theory of Gravitation: 20
 - * Supergravity: 2
 - * Experimental tests of general relativity and Observations of Gravitational Radiation: 1
 - Measurement Science, General Lab Techniques, and Instrumentation systems: (1)
 - * Measurement of Basic Variables

- Time and frequency measurement: 1
- Specific Instrumentation and Techniques of General Use in Physics (2)
 - * Thermal Instruments and Techniques
 - Cryogenics: 2
- The Physics of Elementary Particles and Fields (61)
 - General Theory of Fields and Particles: (27)
 - * Field Theories: 14
 - * Theories of Strings and other Extended Objects: 10
 - * Symmetry and Conservation Laws: 3
 - Specific theories and interaction models; particle systematics: (31)
 - * Unified field theories and models: 25
 - * Models of Electromagnetic Interactions
 - Specific calculations and limits of quantum electrodynamics: 3
 - * Composite Models of Particles:
 - General Properties of quantum chromodynamics: 2
 - Applications of quantum chromodynamics to particle properties and reactions (dynamics, confinement, etc): 1
 - Specific Reactions and phenomenology: (3)
 - * Decays of Baryons: 1
 - * Decays of Leptons: 1
 - * Electromagnetic processes and properties:
 - Electromagnetic form factors; electric and magnetic moments: 1
- Nuclear Physics (11)
 - Nuclear Structure (2)
 - * Nuclear Matter: 2
 - Radioactivity and Electromagnetic Transitions: (1)
 - * Beta Decay; Electron and Muon Capture: 1
 - Nuclear Reactions and Scattering: General: (1)
 - * Resonance Reactions and Scattering: 1
 - Nuclear Reactions and Scattering: Specific Reactions: (4)
 - * Nucleon-induced reactions and scattering: 2
 - * Heavy-Ion-Induced Reactions and Scattering: 2
 - Experimental Methods and Instrumentation for Elementary-Particle and Nuclear Physics: (3)
 - * Radiation Detectors: 3
- *Atomic and Molecular Physics*

- *Classical Areas of Phenomenology*
- *Fluids, Plasmas, and Electric Discharges*
- *Condensed Matter: Structure, Thermal and Mechanical Properties*
- Condensed matter: electronic structure, electrical, magnetic, and optical properties (1)
 - Electron and Ion Emission by Liquids and Solids; Impact Phenomena: (1)
 - * Impact Phenomena
 - Atom, Molecule, and ion impact: 1
- *Cross-disciplinary physics and related areas of science and technology*
- Geophysics, Astronomy, and Astrophysics (931)
 - Fundamental Astronomy and Astrophysics, Instrumentation and Techniques and Astronomical Observations: (86)
 - * Fundamental Astronomy
 - Celestial mechanics: 1
 - * Fundamental Aspects of Astrophysics: 83
 - * Techniques of Observation and Reduction: 2
 - Solar System: (1)
 - * Solar Physics: 1
 - Stars: (24)
 - * Stellar Characteristics: 2
 - * Normal Stars (by class): general or individual: 2
 - * Late Stages of Stellar Evolution: 5
 - Black Holes: 15
 - Stellar systems; galactic and extragalactic objects and systems; the universe: (820)
 - * Stellar Clusters and Associations: 1
 - * The galaxy, extragalactic objects, and systems: 67
 - Groups, clusters, superclusters: 40
 - * Other Objects and Background Radiations of Unknown Origins and Distances:
 - Discrete Radio Sources: 1
 - Quasars: 13
 - X-ray Sources: 2
 - Cosmic ray sources: 1
 - Background Radiation: 24
 - * Cosmology: 671

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