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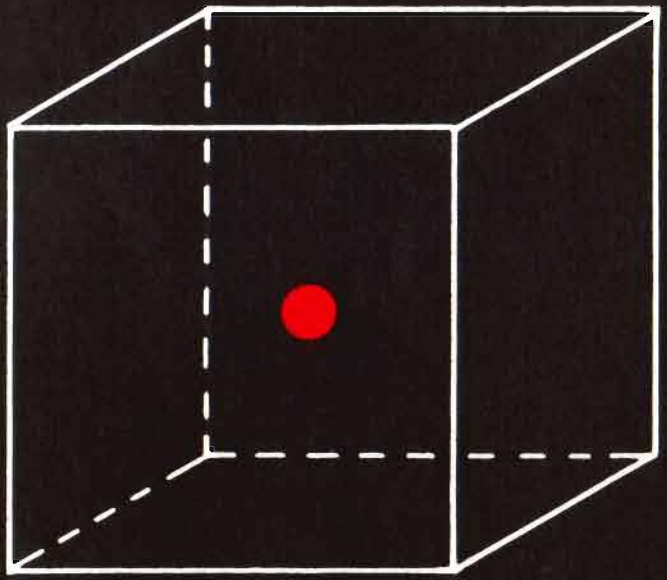
BERNDT MÜLLER

THE STRUCTURED VACUUM
THINKING ABOUT NOTHING



VERLAG HARRI DEUTSCH

Contents

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Preface

Our fundamental understanding of the basic laws of nature has just undergone an almost invisible revolution in that the vacuum has become an integral part of the structure of our universe. This permits the working scientist today to undertake projects only very recently considered the province of science fiction writers. This dialogue gives an account of the understanding of the vacuum as of September 1984.

The reader will encounter in the course of study of this book various aspects of a seemingly contradictory nature. One conflict is that of the academic desire to increase our understanding of the secrets of nature with the seeming banality of our attempts to make practical use of the newly acquired knowledge. Another irritation arises from the human element, in particular, the often childlike joy of the serious scientist - an important source of creative intellectual work - which in instances can ridicule the academic spirit. However, as such is the real world of physical science, and with the intention that the conversation reproduced here may give an adequate impression of it, we have left the "positron gun" standing right next to the probable fate of our universe and the practical importance of electromagnetic waves in the microwave oven.

We would like to thank UCT students, in particular, D. Crouch, G. Hough, G. Littlewort and D. v. Oertzen for their participation in a warm-up discussion which ended with the question:

Are you taking us for a ride?

No. Everything said below is the best scientific knowledge of the authors.

We would like to thank Mary Anne Schütrumpf for typing of the recorded conversation and her help in the preparation of the manuscript. It is our pleasure to acknowledge here the kind support and patience by our families which permitted us to think about nothing.

B. Müller and J. Rafelski
Cape Town, September 1984

Prologue

R: When we sat down to write a book on the vacuum, we realized that by custom we were inadvertently slipping into the style appropriate for an advanced graduate level textbook.

M: But we intended to write a book that is accessible in its content to undergraduate students as well.

R: So actually it should not be a research book; it should be a book in which established concepts about the vacuum are explained.

M: Yes, Jan. What I would think is that it should be a book which contains elements of modern research, but in a way which explains the underlying basic concepts which are important for our understanding of nature, of how nature works, of how the physics works, but not the technical details.

R: I can clearly see an urgent need for such a book. The rapid development of the new concepts about the vacuum over the past years may have not even been noticed by the general public. But today we can begin to study ways of even influencing the laws of nature...

M: Let us talk about all this.

Chapter 1

(The) Vacuum

The Vacuum and the Laws of Nature

R: But is understanding of the vacuum important in order to understand the laws of physics?

M: Indeed so. The surprising thing that we have learnt in the last decade is that the vacuum is very important in understanding the laws of physics and that it comes in addition to the laws of physics. You may have the same set of laws of physics operating in a different vacuum and they would describe very different phenomena.

R: So the vacuum actually provides us with a frame, with a background in which the world is embedded, in which the world of physical phenomena occurs. Is that our understanding of the vacuum?

M: We now consider the vacuum a little bit like a medium in classical physics. You may have the same laws which describe the propagation of light in two different media, but because they are different media, nonetheless the phenomena are very different.

Vacuum = Space free of matter

R: Very nice. So the vacuum, the 'nothing', actually is 'something'. But this sounds so different from the concept of the vacuum that one might have been reading about in an encyclopedia.

M: Well, what would you read in an encyclopedia? You would probably read that the vacuum is a space devoid of matter.

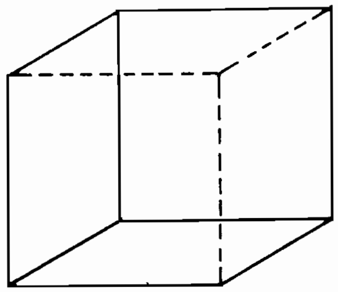


Fig. 1.1: A view of the naive definition of the vacuum as space free of matter.

R: Now, space devoid of matter is taken probably to be the space from which all visible and real matter has been removed by some kind of technical apparatus. So actually vacuum is taken to be a region of space in which nothing is to be found, nothing of any material.

M: Yes, but this concept derives, of course, from history where people attempted to make a vacuum by removing the macroscopic matter from a certain region of space, and it was a true description of what then remains in the era of classical physics, but quantum physics and also relativity have changed that quite a lot.

History of the Vacuum

R: Oh yes, we have gone a long way, but perhaps it would be proper to remind ourselves that the concept of vacuum was actually born long before the birth of modern physics. The vacuum was conceived in order to be able to speak of the absence of matter in the old Greek understanding of nature, of natural phenomena. These concepts were resurrected in the 17th century when technological means permitted the removal of air from vessels, at least the partial removal of it to lower the pressure to such an extent that near vacuum conditions were achieved. Now here , of course, we refer to a material vacuum.

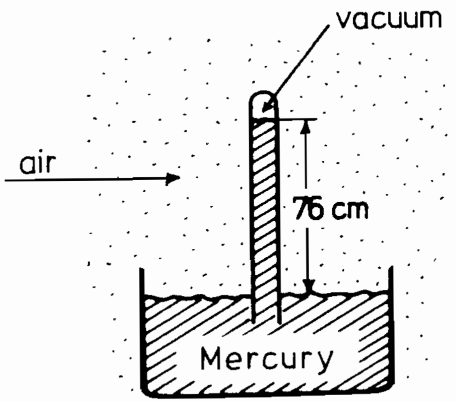


Fig. 1.2: Torricelli proved the existence of the macroscopical vacuum by means of his barometer test.

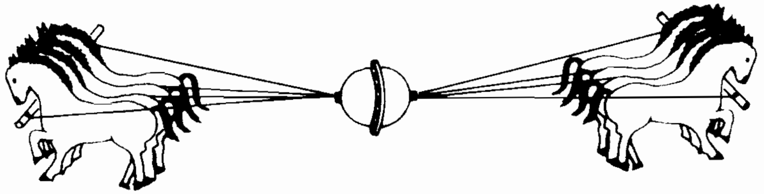


Fig. 1.3: The famous demonstration by Otto von Guericke showing that eight horses are not able to pull apart the two halves of a sphere out of which the air has been pumped.

M: Yes, but the interesting thing is that the old Greek philosophers needed the vacuum for the atoms, which they thought were the substance that makes up matter, to move about in and to rearrange and so on. And when the vacuum was resurrected to be a space devoid of matter in which material bodies or planets or stars could move, then the concept of atoms had been forgotten. Newton certainly did not know about atoms.

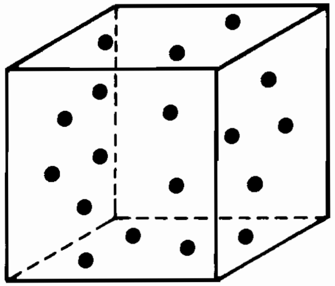


Fig. 1.4: Some ancient Greek philosophers believed that everything is made out of atoms which move within the vacuum.

R: Did Newton already have a concept of vacuum? Did his planets move in a vacuum?

M: I have to confess that I have not read Newton well enough to talk about that. But certainly the scientists in the century after Newton did talk about the vacuum in which planets or the earth or the sun moved.

Speed of Light in the Vacuum

R: I am very much amazed about the difference in the concept of vacuum of the old understanding, and that until twenty years ago it was considered to be a materially empty space, while today we speak of varying vacuum states in which the velocity of light might even have different values. Is it likely that we could create a new vacuum state in which the velocity of light would be different from today's value, or perhaps is our velocity of light actually just a result of being in a certain vacuum state and another vacuum could exist with a much higher velocity?

M: Well, that could possibly be so. We don't know about that. But what we know today, for example, is that if one has a vacuum in which there is a strong electric field or a strong magnetic field, the velocity of light can change. But in all the cases that we know of, the velocity of light will be slower than the one we normally measure.

There are different kinds of vacua!

R: One should realize here that if we were to change the vacuum from one state to another, it would be a catastrophic change in all likelihood, because many properties of physical systems would change, not only the velocity of light. Although note that this would not offer an opportunity to travel faster than light! It is, however, possible that our vacuum is not the only and unique one. So we must now begin to discuss how we actually arrive at the remarkable observation that the vacuum is actually something complex, structured, multivalued and full of information. Maybe we should first try to define the vacuum.

M: Yes. But we have to define it in a way that takes into account the concepts of modern physics, for example that matter is only a certain form of energy, and if we talk about taking matter out of space to produce a vacuum, we also have to remind ourselves that, if we leave behind any energy, that energy might turn into matter and reappear after some time. So I think the first thing one has to do is to explain the relation of matter and energy.

Energy and Matter in the Vacuum ($E = mc^2$)

R: Einstein already recognized at the beginning of the century that all forms of energy are related, matter is a form of energy and that the mass of a body contains a great deal of energy which can be made useful under certain circumstances.

M: Please remind me, Jan: are there cases where one makes use of this?

R: Yes, in the end, of course, in a nuclear fission. There is a very small fraction of a mass of a nucleus which becomes available after a uranium nucleus fission. The intricate physics behind it is, however, that if one has a very large nucleus, one then has many protons together and these protons have a repulsive electrical force which is overcome by the nuclear attraction. However, when we succeed in splitting the nucleus into two pieces by irradiating neutrons on it, then we do gain a substantial amount of electrical repulsion energy because the two fragments fly away from each other and acquire a high velocity due to their mutual repulsion. That energy actually can be seen when one compares the sum of the masses of the fragments with the mass of the original heavy nucleus - the latter is slightly larger.

M: So two halves of the uranium nucleus are lighter, i.e. have less mass than the uranium nucleus. And that is what we use as energy in the nuclear power plant.

R: Yes. Of course, in the sun even a more important phenomenon takes place which is nuclear fusion. Nuclei of hydrogen atoms are fused together and form an alpha particle of four nucleons. In this instance a substantial fraction of the rest mass of the four nucleons is converted into free energy, useful energy which the sun radiates, from which we actually live and derive our sources of utilisable energy like coal, oil, wind and so on. So the fact that mass and energy are one and the same is well established. Indeed burning any fuel we reduce by a miniscule amount the mass of involved elements just in the proper amount required by Einstein's relation. But that means that if we have, for example, an electromagnetic field filling an empty space devoid of matter, that actually this electromagnetic field could, in certain cases, convert to matter, and so we must extend the requirement '<u>space devoid of matter</u>' to the requirement '<u>space devoid of matter and fields</u>'.

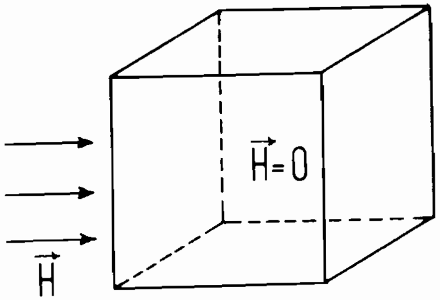


Fig 1.5: Generalized definition of the vacuum as space free of matter and fields.

Quantum Physics and Classical Physics

M: Yes. Now there is certainly a second aspect that is very important to the vacuum and that derives from quantum physics, because the processes in which you materialize energy to matter do not happen on a macroscopic scale. The only cases known in which such a process happens are on a microscopic, atomic scale and those processes are determined by quantum physics. The

way that this works has to do with the uncertainty relation in quantum mechanics.

R: What is quantum mechanics, Berndt?

M: Quantum mechanics is the physical theory of phenomena on the atomic or subatomic scale.

R: So classical mechanics describes the motion of large bodies and quantum mechanics differs from classical mechanics in that it is able to extend this theory to very small dimensions.

M: Well, I would rather state this a little differently. I would prefer to say that classical physics is some kind of limiting case of quantum physics. I mean we know that all the macroscopic phenomena are made up of many, many microscopic phenomena and the motion of a ball is only the motion of very many of its atoms. In that case, all the atoms in principle must behave quantum mechanically, and they do. But if we look at many of them, then we are observing something like an average, something like the most probable quantum evolution of all these atoms. It turns out that one can actually show that classical physics emerges as such a limit from quantum mechanics.

R: In what way does the quantum mechanical motion of an electron differ from the classical motion of a ball?

Uncertainty Relation and Zero-Point Motion

M: The quantum mechanical motion consists of an average over all available paths which can be used. Therefore we cannot make a firm prediction which of the paths will be taken, except in the classical limit in which one path only dominates the physical motion.

R: So quantum mechanics is the more fundamental theory. It is crucial to appreciate that on the atomic scale we lose a certainty about knowing things. We can only express a likelihood that things will happen, and only in the classical limit does this likelihood assume a dimension of certainty. In the domains in which quantum mechanics and quantum mechanical phenomena dominate, we can only speak of the likelihood of something happening. The uncertainty relation expresses this fact quantitatively. It tells you for example that in a measurement the location of a particle and its kinetic momentum cannot be determined simultaneously with infinite precision. If you want to know where this particle is located to an arbitrary degree of accuracy, then you cannot actually say at what kinetic momentum this particle will be found. It is a very vexing problem because classically we like to say, of course, the particle is sitting on the table and it is at rest. Such a statement cannot be made anymore in quantum mechanics.

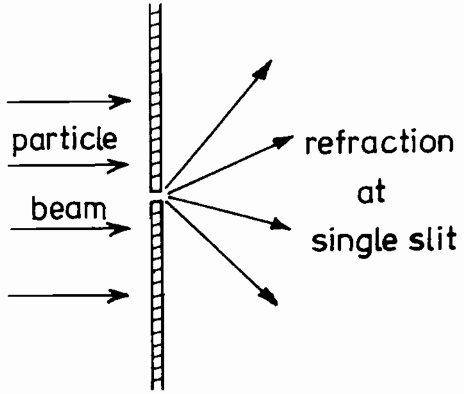


Fig. 1.6: The uncertainty relation between position in space and momentum is a fundamental property of quantum physics. The fixing of the position of a particle with a slit results in a lack of definition of its momentum and thus leads to refraction effects.

M: That has very important consequences for particles which are bound to another particle. Consider that an electron bound in an atom - a similar situation to the earth being bound to the sun, only on an atomic scale - does not fall down into the atomic nucleus because then it would have no momentum and it would be perfectly localized, but quantum mechanics has the built-in requirement that such quantities cannot be well-defined at the same time. So we have some kind of minimal motion of any bound particle - zero point motion is the technical term for it – and particles always must remain in motion.

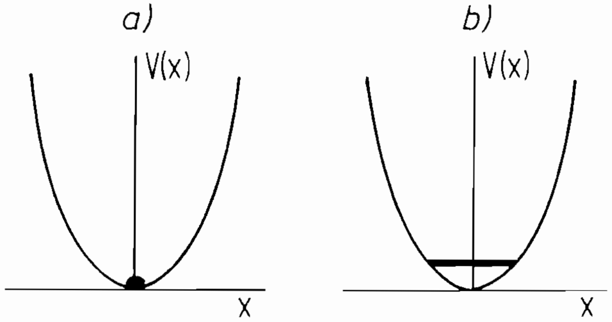


Fig. 1.7: In classical mechanics a particle has the lowest energy when it is resting at the bottom of the potential well (a). In quantum mechanics the particle in the state of lowest energy carries out a zero-point motion (b).

R: So the crucial new concept is that there is an inherent necessity of motion for any bound particle.

Uncertainty in the Measurement of Energy and a New Understanding of the Vacuum

M: Yes. Now more important for the vacuum probably is the other uncertainty relation, namely that between energy and time. This uncertainty relation tells us that it is not possible to measure an energy absolutely

accurately in a finite time. It would take an infinite time to measure energy precisely. If one now has a vacuum and looks at the vacuum for a certain short period of time, then the energy in this vacuum is not well-defined. The amount of uncertainty depends on the length of time of the observation.

R: So the influence of quantum mechanics is only felt if one considers a region devoid of matter for a very short period of time. Even if we were to make every effort to take all forms of energy from this region, we could find some form of energy still inside as long as the period of observation is sufficiently short. We recognize that the vacuum now is very much more difficult to define, and one must leave out all concepts which are classical in nature, classical in the sense that they refer to certainty, and not to probability. So actually taking these two very important points into account – the fact that energy and matter are one and the same and that the absence of energy cannot be assured on a short time scale – we are led to a new definition of the vacuum. How would you phrase this, Berndt?

M: I would define the vacuum now in the following way: Given a certain region of space, I would say that it is in its vacuum state when on the average it has the lowest possible energy.

R: On average you say.

M: Yes, on average because if I look at it for a very short time, its energy might be different from what I expect.

The "True" and The "False" Vacuum

R: In other words, if you perform an observation over extended period of time and you compare two states, two regions of space, then you would say that the one which is lower in energy is the "true" vacuum state. Of course, if you take out all the matter, that is already a state which might appear to you as a vacuum, but there is no guarantee that it is not really a "false" vacuum: it is possible that even after taking out all forms of energy you could, depending on circumstances, arrive in one of two different vacuum states. Is it possible that we even have different vacuum states in different regions of space?

M: Yes, I agree. Even if there are two different vacuum states that have different energy, both may correspond to "local" minima of energy, the true vacuum corresponding to the lowest minimum and the false vacuum corresponding to one of the other minima. There must be a barrier between the two states, and even if the one state has a higher energy than the other one, the probability for it to decay into the second one in a finite time may be very, very small.

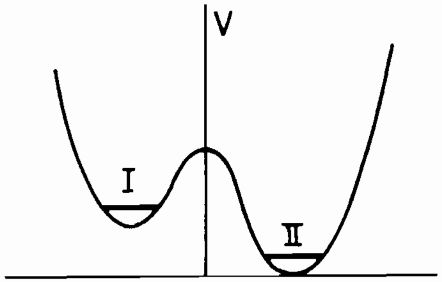


Fig. 1.8: If there are two local energy minima separated by a potential barrier, the vacuum can then remain in the "false" state for an almost unlimited length of time.

R: This reminds me of a chemical reaction. Actually it reminds me more of diamonds and coal. Both are made out of carbon: we all know that diamonds are highly ordered crystals of carbon and that ordinary carbon is a slightly disordered system. Diamonds are transparent, carbon is black. Now both are made out of the same substance but still they are very different in their physical properties, in particular they differ in their energy content. It is not inconceivable that by some external force a diamond could be converted into coal, which could, of course, be very sad for the person who bought the diamond. But this is precisely analogous to what can happen to the vacuum state which has higher energy.

Disintegration of The False Vacuum

M: Yes, but in this latter case the event may be more similar to a chemical reaction. For example, I think one of the most famous examples is dynamite, which was invented by Alfred Nobel who searched for an explosive which is apparently stable. You can put a piece of dynamite on your table and don't have to worry about it. But if you trigger the reaction by putting a little bit of fire, a lighted match, to it, then it will explode and it will release a lot of energy in doing so. In the explosion process the dynamite will go over into a new state, and all its solid material will be turned into gas. So I think if you had two different vacuum states with different energies, they would behave similarly to that. If you sit in the false vacuum state, the one with high energy, and by some accident you were to trigger the transition, then you would release energy and this energy would be set free, ultimately this energy would materialize and would be emitted in the form of particles.

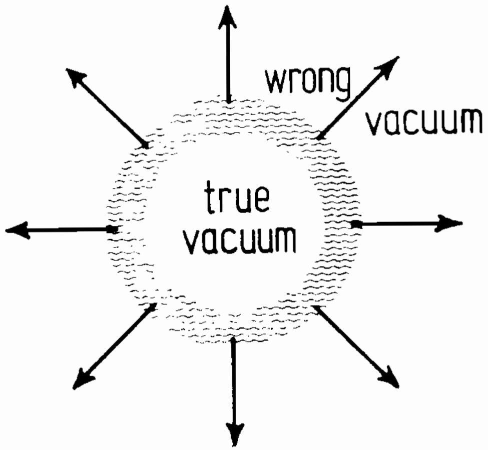


Fig. 1.9: If the transition from a "false" vacuum to the "true" vacuum is triggered, the true vacuum expands in an explosion at the speed of light, releasing the available energy.

R: So what you are suggesting now is that it is possible that our vacuum is a big bag of dynamite and that if we are not careful with it, we might destroy our world.

M: This is not inconceivable and if you look into the current research literature you will find that some theoretical physicists are actually worrying about this thought.

Transition between two Vacua

R: So this book is much more serious than the average reader might have first thought.

M: Yes, it is. Fortunately, it turns out that if you consider the various circumstances accurately, then you will find that today there is not yet an immediate danger. We don't have to worry very much about destroying the vacuum because it happens that the energies that we have available in our big particle accelerators are still not high enough to start the vacuum decay. We know this because in nature particle-particle reactions occur every day. We have high energy radiation coming in from outer space, so called cosmic radiation, and it continually makes interactions around us, even in our own bodies. And these reactions obviously do not trigger the decay of the vacuum. So only when we build accelerators that will test new domains of energy which are entirely beyond the cosmic radiation energy range does the danger arise that we might trigger such a catastrophic event in a particular reaction.

R: Of course, we both know that if dynamite is not lighted properly, it will not explode, and that we have explosives that actually do not like to explode by accident. But once they do explode, they are very devastating. We also know that sometimes a bomb dropped from an airplane can actually land on earth without exploding. What this means is that there is a possibility that even a rather probable event may not actually occur. So it could well be that nature hasn't had many trials yet at disturbing the vacuum in a devastating way. And consequently, we must be very careful when we are approaching the limit to actually not trigger a change in the vacuum state. But of course, what we discussed in the last few minutes will make a difference only if we have a reason to believe that the vacuum could now be in a state which could undergo an explosive decay. Is there such a reason? Why should we believe that we are perhaps not in the ground state, in the basic state of the vacuum?

The Vacuum and the Evolution of the Universe

M: Well, we know that when the universe was created...

R: Do we know about the creation of the universe?

M: Not about the first moment. But what happened even a tiny instant later, we think we know, especially the fact that some time after the moment of creation, the universe was very hot. We know this because we can still observe the background radiation, the microwave radiation which has a spectrum corresponding to a temperature of 3 degrees Kelvin at present, and we can calculate its evolution backwards. We can so infer that this radiation must have been much hotter some time ago than it is today. There are many other reasons why we believe that this primeval fireball existed. For example, certain elements that make up the stars would not have been formed unless the temperature of the universe was very high at some point in time. So we know that at some previous time the universe was very hot and has cooled down since. Now, in physics it is very well known that if the cooling happens quickly, then you often do not come into the phase of lowest energy. Sometimes you get stuck in a phase of higher energy and precisely that could have happened to the vacuum. Should several false vacuum states exist, it would actually be quite likely that ours is not the true one.

The Final Definition of the "Vacuum"

R: Actually that behaviour is a well known phenomenon in physics - just recall again here coal, diamonds, graphite. Thus our worry derives from the fact that our vacuum is not only dependent on the laws of physics, but it is also dependent on the evolution of the universe as a whole. And consequently our former new definition of the 'vacuum' must be still amended: The vacuum state is the state of lowest energy which can be reached given the evolutionary boundary conditions of the physical system. That reminds me, of course, of what everybody knows about motion of a single particle. In order to know where it is going, we must know its initial conditions, its initial velocity and its initial position. The same applies to the evolution of a vacuum state. In order to know in which vacuum we reside today, very likely we have to understand very precisely not only the laws of physics, which we are attempting to find through the study of elementary processes in particle physics, nuclear physics and atomic physics, but also the evolution of the universe as a whole, which is the subject, of course, of the cosmological theories and of astrophysics. All those disciplines probe our understanding of the vacuum and, in the event, may lead to the understanding of our possible self-destruction.

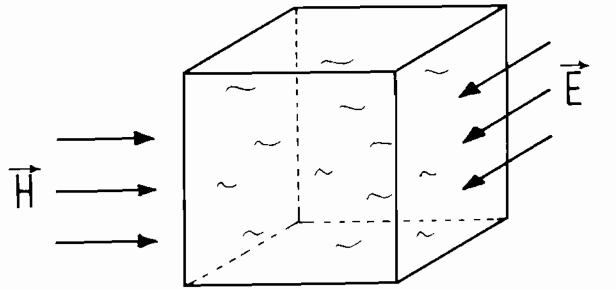


Fig. 1.10: Final definition of the vacuum as an area of space with the lowest possible energy unter set boundary conditions.

Maybe a destructive change of the vacuum is indeed unavoidable. It could well be that some time in the future, nature will generate a very high energy cosmic particle which will at some place in the universe begin the explosive decay of our perhaps unstable present vacuum. So it is of great importance for us to understand the structure of a quantum vacuum. And that is why we have called this book "The Structured Vacuum". We will try in the following chapters to summarize our present knowledge and to indicate the paths of future investigations. We indeed hope that with this book we can contribute to the appreciation of the reasons behind the minds of many people who are devoting themselves to fundamental physics even though this subject is occasionally quite an esoteric one.

M: And to the understanding how other scientists usually not expected to concern themselves with philosophical and fundamental physics, like e.g. astronomers, chemists, and even engineers who build transistors, all contribute to our understanding of the vacuum. Their work has in some ways to do with the structure of the vacuum or is related to it. Understanding the vacuum has great importance for our environment and also for the fate of our civilization.

Chapter 2

The Dielectric Vacuum

The Electrical Forces in Atoms

M: If we want to discuss in more detail the aspects of the vacuum which we have just mentioned in the introduction , one should certainly take as an example one in which we know some of the interactions from experience. Without doubt the interaction which we know best is electromagnetism. So I think we best begin our discussion considering the electromagnetic structure of the vacuum.

R: If we speak of electromagnetic interactions, we must take at least two different types of particles. One might be the atomic nuclei which carry positive electrical charge and the others would be the electrons which are negatively charged. Then of course we immediately have the positrons, the antiparticles of the electrons, which are also positively charged. An atom, as we all know, is a bound state of an electron with the atomic nucleus, and all the atomic properties follow from this. All the chemical molecular properties of matter also derive from the electromagnetic forces among these particles whose effects operate in accord with the principles of quantum mechanics to produce the detailed structure of the matter of our everyday experience.

M: One important aspect of this is that, for example, we can measure and also very accurately calculate the binding energies of the electrons in atoms and molecules. And we know that the binding energy increases as a function of the nuclear charge. For example, the hydrogen atom, which has only one proton within its centre, has the smallest binding energy per electron. If we take the helium atom, which has two protons in its nucleus, the binding energy is about four times as large, when one electron is present.

R: But actually a little bit more than just four times larger because, as we will now describe, the presence of the small localized nuclear charge induces a dielectric polarization of the vacuum in such a fashion as to make the binding of the electrons slightly stronger.

M: To understand this effect, you have to tell our readers about Dirac's underworld, Jan.

Antimatter or Dirac's "Underworld"

R: Yes. Perhaps one should realize that after quantum mechanics was invented, one of the essential steps was to reconcile quantum mechanics and relativity. Dirac at that time invented what is today called the Dirac

equation. This equation describes the quantum mechanical motion of relativistic electrons. However, this equation exhibits very special properties not found previously in the study of the motion of non-relativistic particles. Namely, as we have alluded to in the introduction, in order to have a stable atom, quantum mechanics provides the uncertainty principle and prevents the electron from falling into the nuclear centre. That can be expressed by the statement that there is a lowest energy state an electron can assume when bound to the nucleus. With the Dirac equation this suddenly was no longer true. What one found was that while there were bound states of electrons which nearly corresponded to the previously established non-relativistic states, there also occurred new states which had substantially lower, in fact, negative energy. Dirac interpreted these states later as belonging to antiparticles.

M: Yes, but we have to explain here in what sense we have to understand the physical role of these mathematical, initially totally unreal states. A physical state of total negative energy, even after energy of the rest mass has been excluded, seems at first to be something crazy, but it turns out that you have these negative energies also in relativistic classical mechanics, because the energy of a particle is given by the expression $mc^2/\sqrt{1 - v^2/c^2}$, where m is the mass, v is the velocity of the particle and c the speed of light. Now when you take the square root you can choose the positive or the negative sign, so you have positive and negative energy also in classical mechanics. But this is not important because in classical mechanics a particle can change the energy only continuously; it cannot make a jump in energy ('Natura non facit saltus', as the old sages said). Therefore, if you have a world where all the particles are in positive energy states, they will always stay in positive energy states, because they cannot gradually go to the negative energy states, as there is an energy gap between these states, the smallest positive energy being $-mc^2$.

R: What you really want to say, Berndt, is that we have the freedom of talking about positive or negative energy particles in classical mechanics.

M: Yes, this is exactly my point.

R: So there could be two worlds absolutely symmetric to each other, and when one writes down the Dirac equation, one finds what relation between these two worlds indeed exists.

M: And in relativistic quantum mechanics it is impossible to disregard the negative energies, because in quantum mechanics you can have jumps between different states; transitions between states also occur when they are separated by a finite energy interval. As a result, if you have only positive states in the beginning, an electron in one of these states could make a transition, a jump, into one of the negative energy states. It could then fall into even lower energy states and in the end it would completely disappear while giving off

an infinite amount of energy. And that causes a big problem.

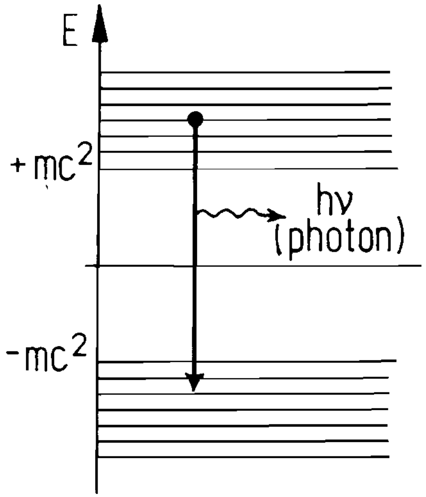


Fig. 2.1: Within the framework of quantum mechanics an electron carrying positive energy would fall down into a lower and lower state under the emission of electromagnetic radiation.

The Pauli Principle and the Stability of Matter

R: That is a big problem as this process would realize the old unfulfilled dream of a perpetuum mobile. So in order to rule out the existence of a perpetuum mobile, Dirac had to invent the antiparticle. The way he did it was to introduce the Dirac sea. He filled all the negative energy states with electrons! This is possible and resolves the perpetuum mobile problem since electrons don't like to coexist with more electrons in the same quantum states. That principle is called the Pauli exclusion principle.

M: Do we understand this principle, Jan?

R: In terms of mathematical equations, very well. In terms of a general statement, also. But there is no classical mechanics analogue to it. The principle of quantum mechanics which underlies the Pauli principle is that when one has a two-electron system, one wishes to describe it in such a manner that when exchanging those two electrons, the mathematical object that describes them, called a wave function, changes sign. This is called antisymmetry of the wave function.

M: If two electrons are sitting at exactly the same point, and if we exchange them, then of course the state doesn't change. But according to the Pauli principle it should change the sign, and something that at the same time remains the same and changes its sign must be zero.

R: Correct. So this actually results in the statement that we cannot have more than one electron in the same state, and that is the Pauli principle. So if we have all these states in which we can put an electron of negative energy, all we need to do to prevent the electron from jumping down to arbitrary lower energies

is to fill the states. In other words, the sea of negative energies is full of particles.

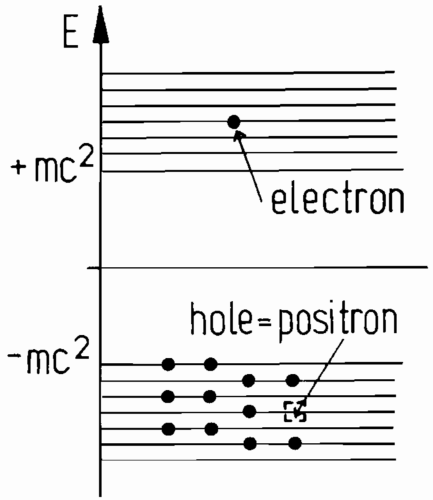


Fig. 2.2: Dirac's "underworld" - all states of negative energy are normally filled with electrons. The Pauli principle prevents electrons with positive energy from falling down. A vacant state of negative energy (hole) appears as an 'anti'-particle with the same mass but with a positive charge (positron).

Symmetry between Matter and Antimatter

M: The introduction of Diraac's sea on the one hand solves Dirac's problem, namely it provides the reason why electrons don't fall into the negative energy states. On the other hand it also poses a new problem, namely if you have infinitely many electrons in the negative energy states, this Dirac sea carries an infinite charge.

R: Yes. But then that will be solved by a similar consideration in which you fill the positron negative energy sea.

M: I see. So you also have a Dirac equation for positrons, which is the same equation, and differs only in that the particles have opposite charge. This Dirac equation also has positive and negative energy states. If you have positive energy positrons, then in order to prevent them from falling down, you also must have a sea of negative energy positrons. As a result, the charges of the two Dirac seas of electrons and positrons cancel exactly.

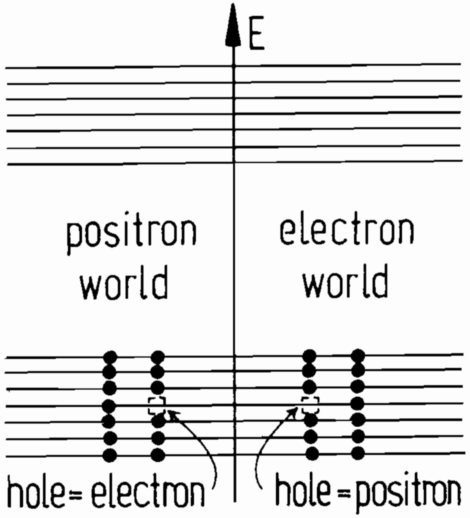


Fig. 2.3: Because of the symmetry between the world of electrons and the world of positrons the Dirac vacuum is totally uncharged.

R: Yes. That is in essence the reason why we do not see an infinite charge, and at the same time we can have all the negative energy states filled with particles.

Vacuum Polarization

M: Now I can also see why there could be an effect when you introduce a nucleus, because the charge of the nucleus will interact with the electrons and positrons in the Dirac sea.

R: There is nothing particular about a nucleus, any electric field will do that. The nucleus, of course, generates an electric field and displaces electrons and positrons differently.

M: It will attract the electrons and will repel the positrons.

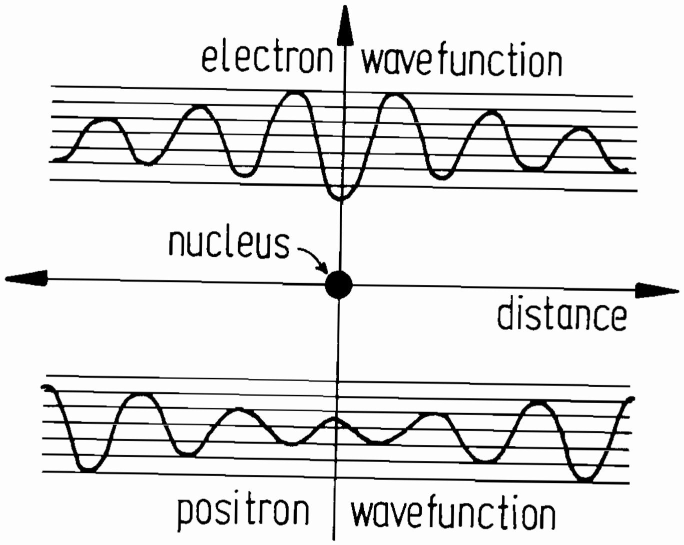


Fig. 2.4: An atomic nucleus attracts electrons with positive energy (positrons with negative energy) and repels electrons with negative energy (positrons with positive energy).

R: Correct. And consequently we have exactly the same situation as we have in a macroscopic medium.

M: Only now it is a little different, because the electrons in Dirac's underworld, in the Dirac sea, have negative energy. And that means that if you have a force which attracts them, they like to move away. Crazy, huh?

R: No, it is not crazy. There is an extra sign in this picture, and if one works it out mathematically one arrives at the result that the displacement charge density in the vacuum due to an applied electrical field will actually strengthen the electrical field rather than weaken it. Normally one would expect, especially if one thinks of a behaviour of a polarizable medium, that any electrical field applied to it would be weakened by the displacement charge generated.

M: That is the typical case with an electrolyte. When you apply voltage to an electrolytic liquid - such as water or acid in a car battery - the polarization weakens the field.

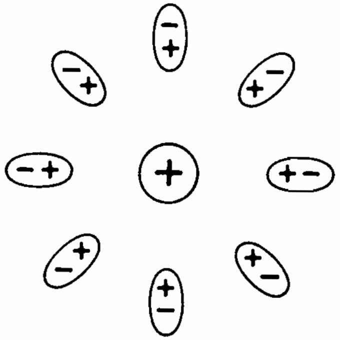


Fig. 2.5: An atomic nucleus attracts the positive charges present in the vacuum and repels the negative charges because they belong to particles with negative energy. The vacuum polarization thus strengthens the electrical field of the atomic nucleus.

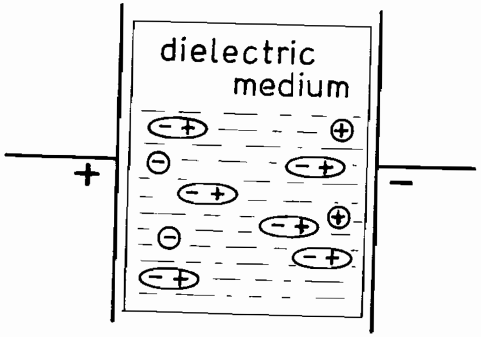


Fig. 2.6: In a material medium the real charges are polarized in such a way that they weaken the applied field.

Renormalization of Charge

R: Yes. That is a very well established experimental fact. And we, of course, must expect the opposite now of a vacuum, because of the change in sign which arises from the sign of negative energy states. Thus we must compute such quantities very carefully. When this is done, the first result one finds is that there is indeed an infinite contribution to the displacement charge. This, however, does not disturb the theorist, because he realizes that the definition of the unit of charge is subject to arbitrary renormalization. All charges we observe are charges which we measure in the vacuum. And consequently if a vacuum acts back on the charges in such a way as to change the value of a charge, that can be absorbed into the definition of charge as a physical quantity.

M: But only if it affects every charge in precisely the same way, I mean, if it multiplies every charge by the same factor. So if you add two charges, then the way that they are affected is exactly the sum of how the individual charges are affected.

R: That indeed will be true if it is dependent only on the structure of the vacuum and not on other phenomena, because then the vacuum response to any charge will be the same. And actually one can prove a theorem which shows that this is true in general. So the observed electrical charge is derived from a bare electrical charge which is then renormalized to the physical value by the polarization of the vacuum.

Vacuum Polarization is Observable

M: So now we have understood why in the presence of an atomic nucleus the vacuum will be polarized. It will be polarized similar to a dielectric medium. Of course, it would be interesting to measure this, to do an experiment and really test that this is so.

R: What you really mean to say now is that the phenomena which we have been talking about will also make a contribution which is not only absorbed in the renormalization of a charge, but which implies a modification of the inverse square law of the force between two charges.

M: Yes, because if you have a change in the space distribution of charge, you cannot reabsorb it into the charge. Only the total charge can be absorbed in that way. And hence a polarization, a displacement charge, will have an observable effect.

R: That is actually what we find, and now all we need to do is to find a system in which this fact becomes easily visible.

M: Yes. But for that it is very important to know what the range of this displacement charge is. I mean you

have to select a physical system that has as its typical dimension the size of this displacement charge.

Range of the Polarization Energy

R: Now clearly it cannot be true that the vacuum polarization effect is visible for macroscopic distances, because then we wouldn't have experimentally verified the Coulomb law of electric forces in the first place. So it must be something which has a short range, a microscopic range perhaps. Now what is a typical scale of length which one has in this problem?

M: Well, we can estimate the typical scale of length by considering the origin of the displacement charge in the following way: the electrical field of the nucleus is pushing away the negative energy electrons and attracting the negative energy positrons. In terms of the normal vacuum without the presence of the nucleus, the vacuum polarization corresponds to the creation of one or more virtual electron-positron pairs for a very short time or over a very short distance. And the energy it takes to do that is of the order of twice the rest energy of the electron, which is equal to its mass times the velocity of light squared.

R: And the momentum that such a pair would have to carry would be of an order of magnitude of twice the rest mass of the electron times the velocity of light.

M: Yes, so now you can take the uncertainty relation which tells you that the product of the uncertainties in momentum and position is of the order of Planck's constant, $\Delta p \cdot \Delta x > h$, and you will find that the typical length over which this will happen is Planck's constant divided by twice the rest mass of the electron times the velocity of light: $L = h/mc$. This distance is about a few hundred times larger than the size of the nucleus and it is about 100 times smaller than the size of a hydrogen atom.

R: And since the size of a hydrogen nucleus is of the order of what we call one Fermi (10^{-13} cm), the size of the displacement charge will be of the order of a few hundred Fermis.

M: Right. So we need a physical system in which we can do an experiment and which has a size of a few hundred Fermis. Obviously it will not be a hydrogen atom.

R: How large is a hydrogen atom, Berndt?

M: It is about 50 000 Fermis, so, as I have already said, it is about a 100 times larger than the dimensions of the vacuum polarization.

R: Now, can one imagine that we could make the hydrogen atom smaller?

M: Yes, we can by using instead of the hydrogen nucleus a heavier nucleus with a higher charge that attracts the electron more strongly.

R: That is a very interesting suggestion. But then, of course, we have not just a single electron in the atom, we have as many electrons as there are protons in the nucleus.

M: For example we can take a lead atom with 82 electrons. This would be a very nice case because in this atom the most strongly bound electron has a radius of about 700 to 800 Fermis. However, as you just said, we would have to solve for the coupled motion of 82 electrons. And it is very difficult to understand exactly the energies of these states, as you know by experience.

R: Do we have an alternative way of making the atom smaller?

The Muon: the Electron's Heavy "Brother"

M: Well, it also turns out that the size of the hydrogen atom is determined by the mass of the electron.

R: And by the strength of the coupling, of course. If the coupling would be much reduced, the atom would be much larger; if the coupling were much stronger, then the attractive force would be much stronger and the atom would be much smaller. So there are two qualities which determine the size of an atom: the strength of the electrical charge and the mass of the electron.

M: Yes. Now fortunately it turns out that the electron comes in more than one kind. We know a heavy electron which is called the muon.

R: Do you know why there is a heavy electron?

M: It is interesting that this simple question about the reason for the existence of the muon, which has been known for more than forty years now, has still not found an answer. At present we have no explanation of why there is such a particle.

R: So for the purpose of this discussion we must assume that an electron has a heavy brother called the muon, which has a mass about two hundred times larger than the electron's mass. Then the size of a muonic atom turns out to be about two hundred times smaller.

Muonic Atoms

M: Yes. So one might first consider using a hydrogen atom with the muon instead of the electron. Unfortunately, it turns out that a hydrogen atom with a muon is not stable. It will attract another hydrogen atom and form a muonic hydrogen molecule, which has fascinating properties but is not suitable for a measurement of vacuum polarization.

R: So we must take a nucleus which doesn't form a molecule. Helium contains such a nucleus. As we all

know, helium is a noble gas and consequently it doesn't form a molecule.

M: Yes. Also, the helium nucleus has two protons. So if there is one muon bound, then the system will remain positively charged and it will not approach another atom. It will remain just an ion, a helium nucleus plus a muon.

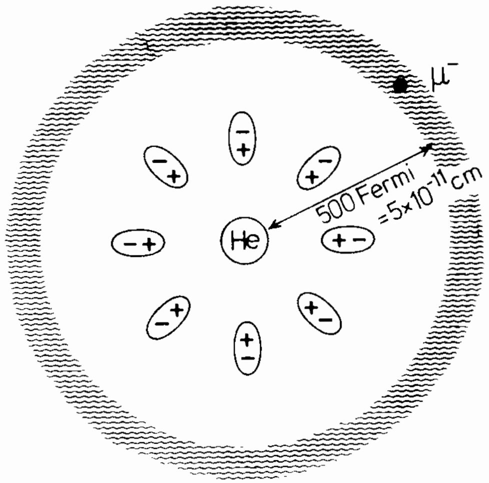


Fig. 2.7: The muonic helium atom is an ideal system for experimentally measuring the vacuum polarization because of its very small size.

Life-Time of the Muon

R: So we actually have an ideal system to study vacuum polarization. It consists of a nucleus of a helium atom and a single muon in its orbit. Now tell me, does this system live long enough to allow for an observation? Are muons stable?

M: You raise a very important point. In fact, a muon is not a stable particle, otherwise muons would be all around us. We would actually have muonic matter instead of electronic matter. But this is not the case. Muons decay in about two microseconds, i.e. two millionths of a second, and in that decay process the muonic helium atom is destroyed. Fortunately the time it takes to form such an atom is much shorter. The muon is captured by a helium nucleus and falls into its lowest state within about one picosecond, which is a period one million times smaller than the time it takes for the muon to decay. So in terms of this scale, we have lots of time to do an experiment on muonic helium atoms.

R: In a way the decay of muons resembles radioactive decays which we find in nature quite often. Actually, human bones are full of calcium, some isotopes of which are radioactive with an average lifetime of about one billion years. As a man lives on the order of a hundred years, that means that during the human lifetime a fraction of less than one millionth of all radioactive calcium in the body would decay. The story of muonic helium is exactly the same. During its formation time only a fraction of one in a million or so of all muons will have disappeared. That does not bother our experiment at all.

But let us now return to our original investigation of the vacuum. Having identified the best system to perform a measurement of the vacuum polarization, the question is: Precisely what kind of effect do we expect? How large will this effect be?

Measuring the Vacuum Polarization in Muonic Helium

M: Now, what we know is that the effect must be much smaller than the interaction between the helium nucleus and the muon, because the displacement charge contained in the vacuum polarization can be calculated to be about one thousandth of the charge of the muon itself. So what we expect is that the effect on the energy of a given state in muonic helium will be of the order of one thousandth of the total binding energy of such a state.

R: Another thing which clearly is a distinctive feature is that the deviation from the Coulomb law of interaction between the muon and the nucleus will be seen only at short distances. Therefore only those muonic states which have a capacity to probe the short distances will be measurably affected.

M: In this respect, muonic helium is a very good system for a second reason: There are states which have quite different wave functions (more precisely states which have different angular momentum of the muon going around the nucleus) though they have almost the same energy. So if the vacuum polarization acts on these states in a different way, then one expects a splitting in the energy of these states, and one might be able to observe that splitting to a high degree of accuracy.

R: This is actually what has been done experimentally. The observed splitting turns out to be just what theory predicts, of the order of one thousandth of the binding energy.

M: How can one measure this energy so accurately? It must be quite difficult.

R: Not really. Since the energies in muonic atoms are determined by the scale provided by the muonic mass, which is two hundred times larger than electronic mass, the shift, which we just discussed to be of the order of one thousandth of it, is actually about one fifth of the energy found in electronic helium. Consequently, it just falls into the range of energies which are found in common molecular physics, and for which laser sources of radiation have been constructed.

M: So the idea of the experiment is that one has a laser with a tunable frequency, and one tries to excite muons from one of the two split states to the other

just by the process of absorption of the energy of the laser light.

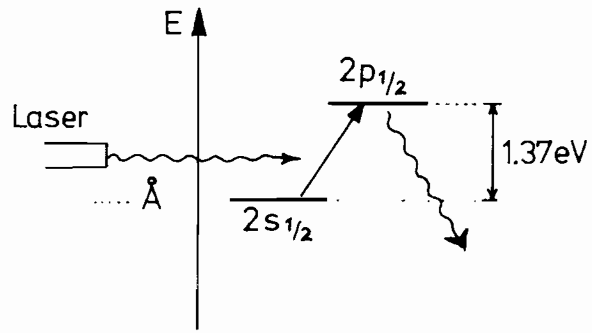


Fig. 2.8: The splitting of the 2s and 2p levels within the muonic helium atom is measured by exciting suitable atomic states by means of a laser.

R: Quite right. Of course, in order to be able to do so, one requires that these states be long-lived. But nature has been very kind in this respect, and has provided us with a meta-stable state, the so-called 2s-tate of the muon which, due to the effect of vacuum polarization, is slightly more attracted to the nucleus than the so-called 2p-state, and the energy difference between them falls just into the frequency band of tunable lasers. Several years ago an experiment was carried out in just this fashion. It is remarkable that we have a phenomenon here in which the presence of vacuum polarization is essential in order to make the experiment feasible. But vacuum polarization as such is an effect which is found in many other atomic systems, and knowledge of vacuum polarization is an essential ingredient in the precise determination of atomic energies.

M: So today we can regard vacuum polarization as an experimentally well established physical phenomenon which has been quantitatively confirmed by experimental tests.

Other Interactions

R: It has been confirmed to such a degree of precision that we can convincingly argue that our understanding of the interaction between electrically charged particles is very well established indeed. Of course, we can only say this about the structure of the vacuum as far as electromagnetic interactions are concerned. As everybody knows, in nature there exist other interactions. For example, gravitational binding is essential for the creation of planetary systems and so-called weak interactions are essential for the natural radioactivity of atoms...

M: ...and strong interactions bind atomic nuclei together, which is necessary in order to make a many-electron atom.

R: Yes, so there are many interactions, but the best known is the electromagnetic one. We have now established that because of electromagnetic interactions there is a displacement charge in the vacuum. This is the first vacuum structure which we have discovered. But there is something more to it than just that.

Chapter 3

The Charged Vacuum

M: We have learnt that the vacuum can have a structure, and we have seen that experiments prove that this is indeed so. Let us now try consider if the vacuum can change its structure under appropriate conditions.

R: What do you mean by "changing its structure"?

M: Well, we discussed that the vacuum may have different types of structure, and that it may be caught up in one structure, and maybe if conditions changed, it could decay into another structure.

R: What you are referring to is what we called a state, as there can be two different vacuum states which have different structures.

The Electrical Charge of the Vacuum

M: Yes. The structures must be distinguished by some property, and if we discuss electric or electromagnetic vacuum states, one of the most important properties certainly is charge.

R: We decided that in the Dirac sea picture the charge of the vacuum is zero.

M: But this had to do with the fact that the vacuum was only polarized by the relatively small charge of the helium nucleus.

R: And was symmetric initially between electrons and positrons.

M: That is correct.

R: How do we break the symmetry?

M: Well, we already broke the symmetry by introducing the field of a nucleus, because the nucleus has a positive charge and it acts differently on positrons and electrons.

R: Therefore in principle there is no reason to believe that the charge of the vacuum is zero anymore.

M: That is right. Now how can it become charged?

R: When something is able to absorb a charge.

M: But we have charge conservation.

R: Well, that is OK if the vacuum is charged. We must measure it in a box in which the nucleus produces real charges, while the opposite charge can be pumped out of this box by some machinery. So then the vacuum surrounding the nucleus in the volume of the box would actually be charged.

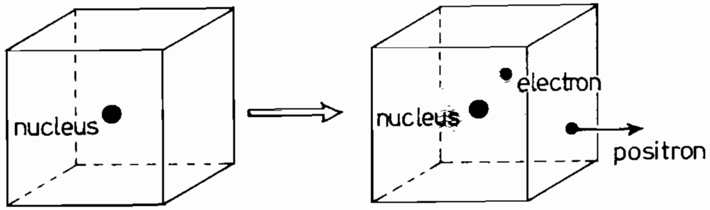


Fig. 3.1: If the electrical field of an atomic nucleus is strong enough, real particles could be produced from the vacuum. The local vacuum near the atomic nucleus is then negatively charged as a positively charged particles are repelled and escape.

M: Now, if the vacuum is really charged, we would not only have what we called before the virtual vacuum polarization, but in addition a kind of real vacuum polarization, so that the total charge contained in the vacuum is different from zero.

R: That is quite possible. Remember we had to go through some lengthy discussions before we were able to argue that the vacuum charge is zero, that there is only a displacement, a polarization, charge.

Charged Vacuum - or not?

M: Now there is, of course, the question whether all this really can happen. I mean, couldn't it be possible, when the field becomes so strong that it tries to change the structure of the vacuum, that due to the polarization of the vacuum the electrical field will become weaker again, so that there is some kind of self-modification of the electric field, some inherent limitation which tells us that a real charged vacuum cannot actually occur.

R: Phenomena of this kind are well known in nature, but the opposite, namely occurrence of a change in the structure of the state when forces are exercised, is also well known. Whether there is a screening or an anti-screening effect is a question of the details of the theory.

M: And depending on this one can have saturation or not.

R: Correct. So in order to be sure that a charged vacuum will be the result of an ever-increasing strength of electric field, we must investigate carefully the theory of the interaction of electrons and positrons in a given electric field.

M: I recall that when we discussed the vacuum polarization in the muonic helium atom, we said that the effect of vacuum polarization is opposite to what one would naively expect, that in fact it tends to increase the electric field.

R: And this indeed continues up to the point where the vacuum polarization becomes real. The 'virtual' vacuum polarization always strengthens the applied electrical field. However, there may be other effects which could counteract this tendency.

M: But these effects have been very carefully investigated, and it has been found that they make only a very small correction, and certainly cannot keep the electrical field from becoming so strong that the vacuum polarization becomes real.

R: If this is the case, then we have no reason to doubt the possibility of forming a charged vacuum - the new structured vacuum - with a sufficiently large nuclear charge.

M: This is our present understanding. It would be very interesting to observe this effect experimentally, in order to find an example where the structure of the vacuum state actually changes.

The Sparking Vacuum

R: Now, we both know that when we apply a very strong electric field to insulators, these insulators can spark occasionally. This is due to some remaining residual electrical conductivity in the insulating material, which can lead to an avalanche of ionization.

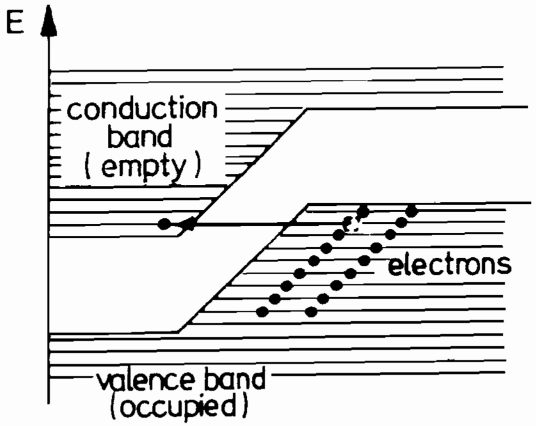


Fig 3.2: A high electrical voltage results in the "penetration" of an insulator. In this process electrons jump out of bound states (valence band) into the conduction band.

M: And the threshold that is necessary to create an electron-positron pair in the vacuum plays a similar role to the threshold that must be overcome in an insulator to make a spark.

R: Right, we can view the states of electrons and positrons as being analogous to the conduction and valence bands of insulators. As soon as there is enough strength in the electrical field to bridge the gap between the electron and positron states, this will create an electron-positron pair. We would expect the vacuum to spark not only in the vicinity of atomic nuclei, but also if we were to apply a sufficiently strong constant homogeneous electrical field to the vacuum.

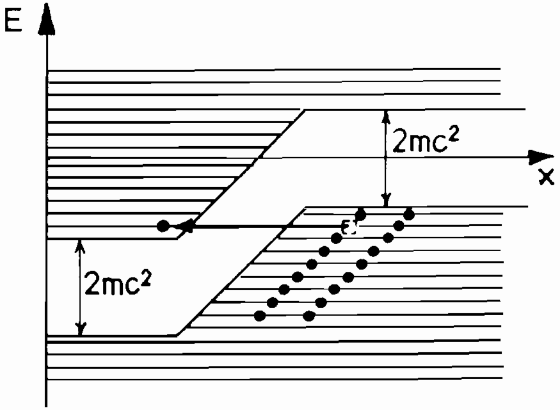


Fig. 3.3: A very strong electrical field is capable of producing electron-positron pairs from the vacuum. States of positive and negative energy play the role of valence and conduction band.

M: This is indeed the case. But it turns out that, if one calculates the probability for such a pair production to occur, one finds that in normal macroscopic electrical fields, even the strongest ones that can be produced, this probability is so small that we would not be able to observe it in a lifetime.

R: The essential point, as we have already discussed, is the strength of the electrical field at subatomic distances. We have identified during the discussion of the vacuum polarization that the critical distance is of the order of 400 Fermi. So now we have to manage to change the electrical field from basically zero to the required value over a similar distance. This is of course impossible with macroscopic fields. But it is possible with the electrical field of a super-heavy nucleus.

Supercritical Atomic Nuclei

R: But tell me, Berndt, isn't this so far remote from what actually occurs in nature that we have here an exercise in ivory-tower physics?

M: No, this is not so. Of course the experiment to produce positrons from super-heavy nuclei would itself be an ivory-tower experiment. But we are not really investigating such a process for its own sake, but what we want to show is a principle, a fundamental principle, namely that the vacuum state can have different structures. We want to prove in one instance where we understand all the interactions and where we can calculate everything exactly, that nature behaves as we expect on the basis of our concepts.

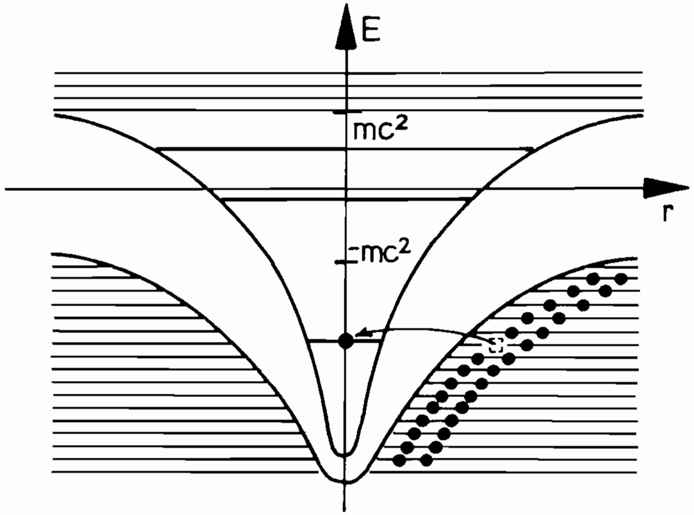


Fig. 3.4: The electrical field near a superheavy atomic nucleus results in the spontaneous production of a electron-positron pair ("decay of the neutral vacuum").

R: What you want to say, Berndt, is that in many instances where we expect such changes in the vacuum to take place, we do not have such a firm control over the circumstances as we have in a super-heavy atom.

M: But this is a typical way to proceed in science. If one wants to prove a general principle and to test the fundamental concepts on which much of further reaching understanding is built, one takes a very special case where it is possible to do an experiment, and where one can control all the details, to make predictions and compare them with the experimental results.

R: It is in a way similar to Galileo's experiment of dropping a heavy and a light stone from the tower in Pisa. By demonstrating that two objects of different mass arrive at the surface of the earth at the same time, he demonstrated the principle that the velocity of a falling object is independent of its mass.

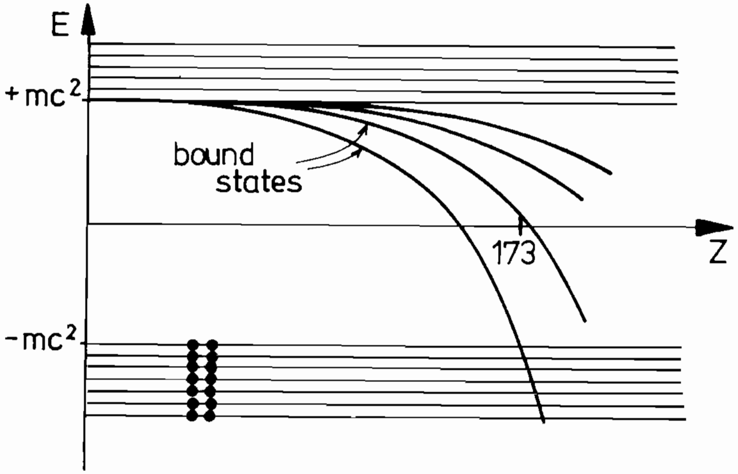


Fig. 3.5: The vacuum polarization becomes real when a bound electron state dives into the sea of

M: But let me come back to the experiment. When the electrical field is made sufficiently strong so that the vacuum polarization becomes real, then, due to charge conservation, we must get rid of the balancing charge, and therefore, during the process of change of the vacuum from a neutral to a charged state, some charge must be emitted. And if in the vicinity of the electrical field of the nucleus, the vacuum carries the charge of an electron, the emitted particle must surely be a positron.

R: And one can show that this positron must have a very well defined energy. The electrical field applied determines how large this energy will be. So one can predict, depending on the strength of the electrical field, what the energy of the positron will be. This prediction can be tested in experiments which employ various different electrical field strengths.

Experimental Evidence of Vacuum Decay

M: Now, nuclei with a sufficient number of protons to make a field which is strong enough to produce a real vacuum polarization do not exist, so we have no way of doing the experiment with an existing nucleus. But what one can do is to hurl two very heavy nuclei, like uranium nuclei, at one another so that they come very close together. A small region of space then contains a total of 184 protons in close proximity, and during the time that the nuclei spend together, one may hope to

see the transition from the neutral vacuum to a charged vacuum. It has been argued that there is not enough time to observe the vacuum decay if the two nuclei simply fly past each other. The reason lies in the uncertainty relationship again: if the time available for the vacuum decay is very short, then the energy of the emitted positron is very diffuse and one cannot distinguish positrons emitted by the decaying vacuum from the many positrons produced by other processes.

R: Fortunately the attractive nuclear forces help us out here. These energies which are normally responsible for the stability of the atomic nuclei also cause an attraction between the uranium nuclei flying past each other if their surfaces come into contact. Then a giant "double uranium" nucleus which could be relatively long-lived may be formed. Such "nuclear molecules" were discovered quite a long time ago, but their possible creation on the impact of two very large uranium nuclei was not generally expected. If the nuclear molecule is created, then there should be enough time for the transition from the charged vacuum to take place through the emission of a positron with a precisely defined energy.

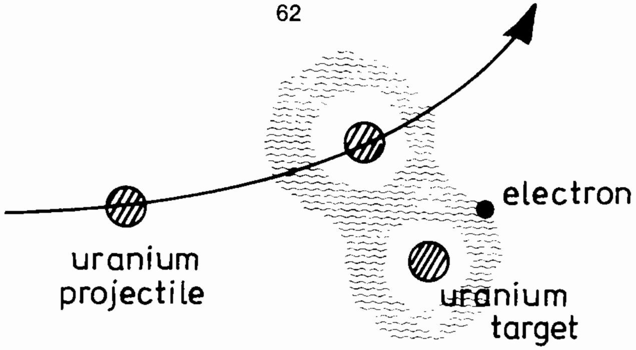


Fig. 3.6: In a collision with two heavy nuclei a super-heavy "quasi-atom" is created for a short time.

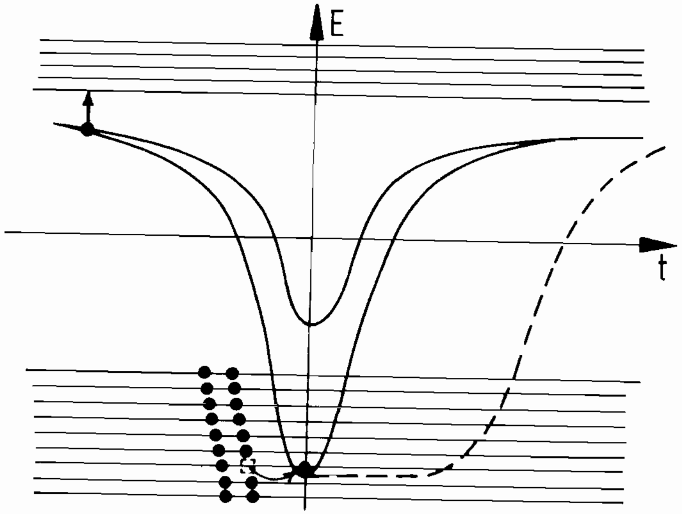


Fig. 3.7: During the collision of two very heavy atomic nuclei (e.g. uranium with uranium) a bound state of electrons dives temporarily into the sea of electrons with negative energy (Dirac's sea) and spontaneous formation of an electron-positron pair then ensues. The positron is emitted with a well defined energy.

R: Such experiments have been performed for quite some time now at the GSI laboratory near Darmstadt. Here sharp lines have indeed been found in the positron spectra the energy of which coincides more or less with the energy calculated for the positrons in the vacuum. However, further experiments are needed to ascertain the delicate nature of the observed positron lines.

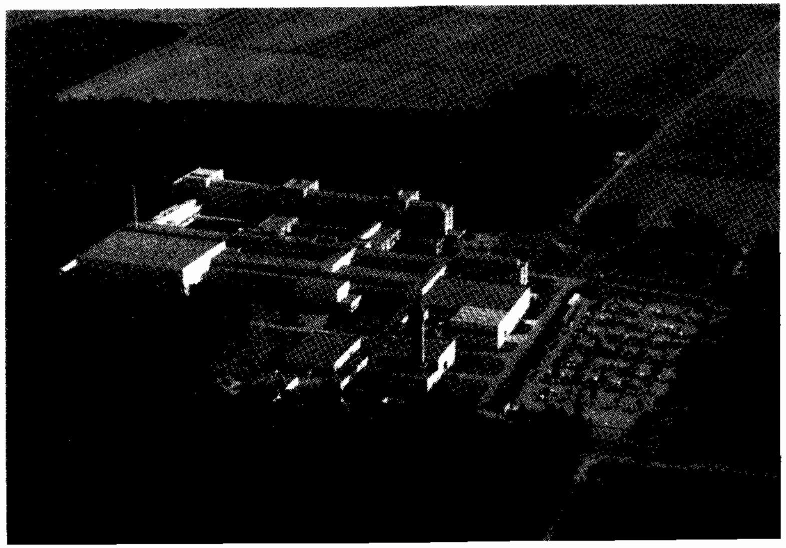


Fig. 3.8: Aerial view of the heavy ion accelerator laboratory GSI at Darmstadt, West Germany, where experiments are conducted in which very strong electrical fields are created in heavy ion collisions.

(Reg. Präs. Darmstadt, Nr. 2346/82)

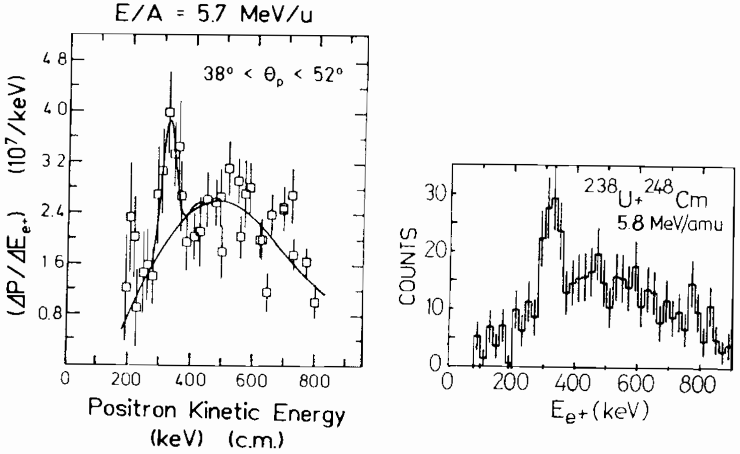


Fig. 3.9: Sharp lines in the positron spectrum from heavy ion collisions as observed at GSI.

M: Although all the experimental results seem to be consistent with the theoretical predictions about the decay of the electrodynamic vacuum, there are very difficult problems of nuclear physics associated with collisions of nuclei when their skins touch each other. Thus at present other experiments are being made to unravel the details of the nuclear structure involved.

Is there a Positron "Gun"?

R: The time has come to ask why we expect only one positron. Perhaps we should believe that our new vacuum state acts like a positron gun and positrons continue to be emitted in large numbers when the vacuum state has decayed.

M: That possibility sounds quite exciting. However, it contradicts the basic idea of Dirac's underworld, which is based on the Pauli principle which tells us that only one electron can occupy a given state. If we have just one state bound sufficiently strongly so that we can make an electron-positron pair without the expense of additional energy, then we cannot make more than one pair.

R: But if we increase that electrical field even further, then we may expect that just as we had a first spark, further sparks will occur. And so with stronger and stronger electrical fields, more and more positrons can be emitted. But we must realize that the counterbalancing charge of the vacuum always remains localized in the vicinity of the nucleus...

M: ...and screens the strong electrical field of the nucleus.

R: Aha; so actually we now do screen this source of electrical field by the real vacuum polarization.

M: Yes. This is the fundamental difference between virtual vacuum polarization and real vacuum polarization. The former anti-screens or increases the strength of the field, whereas the real vacuum polarization screens the field.

R: If this is the case, then of course we can never produce more positrons than there are protons in the source of the electrical field. That is a very strong limit to the number of positrons we can produce which will limit the effectiveness of a positron gun based on formation of the charged vacuum state.

M: This is certainly true. But this discussion takes us far beyond the limits of present experiments, and we will probably not be able to make more than one or two positrons in one heavy ion collision in the foreseeable future.

R: But as we both know, science has made great strides, and what is not possible today often becomes possible tomorrow. So we should be very careful about setting limits which are of no fundamental relevance. The velocity of light is a fundamental limit to the motion of all physical bodies. However, the strength of an electrical field we can create over a small volume does not know any limit. So we may expect that at some future time someone will find a very clever way of creating a very strong localized electrical field.

M: On the other hand, although we don't have the possibility of making a positron gun, one could ask whether the electrical field could not produce other particles like muons...

R: ...to have a muon gun? Or perhaps even a quark gun?

M: Well, we cannot produce more positrons when all the electron states are filled because the Pauli principle forbids the production of new electrons, but the Pauli principle does not forbid us to create muons instead.

R: Yes, but of course, even if we were to make muons, they would also be limited by the Pauli principle, which also applies to muons. But we must investigate beforehand whether the electric field will be sufficiently strong to produce particles two hundred times heavier than electrons.

M: Well, probably not, because as we have discussed in the context of muonic helium, the orbits of muons around the nuclei are much closer to the nucleus than those of the electrons. For a nucleus with a very strong electrical field, the orbit will be so close that the muons will actually be inside the nucleus, and no longer feel the very strong electrical field to its full extent.

R: What you recognize again here is the fact that the muon sees structures which are two hundred times smaller. Consequently if the nucleus has a size of 15 Fermis in diameter, as is the case of the uranium nucleus, muons explore, in their most tightly bound orbits, more the structure of the nucleus than the 1/r-law of electromagnetic interaction between the nucleus and the muon.

Vacuum Decay and Other Elementary Particles

M: So muons are not a good probe of strong electrical fields. Actually, in light atoms, as we have discussed, they are ideal probes. In the circumstances required to study the spontaneous decay of the vacuum, they are not. Actually, I can carry it further. If we were to discover an electrically charged particle which is much lighter than the electron, this would be a great help indeed, because then we could form the charged vacuum at an earlier point. Unfortunately the electron is the lightest charged particle that we know of and very likely there are no lighter charged particles.

R: The important point to keep in mind here is that in order to facilitate the vacuum decay, we need particles which are particularly suitable given the form of the electrical field generated by the colliding nuclei. Probably the best case would be a heavy electron about five to ten times lighter than a muon.

M: So the presently known zoo of elementary particles does not give us good opportunities of observing the vacuum decay.

R: Yes, indeed - it is a very nice and rewarding circumstance that an electron just has sufficiently good properties and offers us the possibility of generating the change of the vacuum under laboratory conditions.

M: Isn't it amazing that, depending on what problem one wants to tackle, on what kind of concept one wants to test in physics, one always finds some particle which is so kind to have the right size, the right mass, the right energy and the right properties to permit an experiment.

R: No, I think it is not amazing. I think that the questions asked arise merely because of the existence of the particles. If electrons were not there, we probably never would have been confronted with the problem of the vacuum decay. It is as if the knowledge we have creates the new questions we must ask. It has been the desire to understand the electronic orbits in superheavy atoms that led to the development of the theory of the charged vacuum. And if we have the knowledge of the vacuum decay in an electromagnetic interaction, that knowledge permits us to ask how relevant this is for other interactions in other circumstances and this will doubtlessly lead on to new and important insights about the world around us.

Further Interactions and the Vacuum Structure

M: Are there other interactions which are similar to the electromagnetic interaction?

R: Today we believe that all interactions have similar properties. The remainder of this book will be concerned with them, and we will show how the knowledge we have gained about the possible vacuum structure of the electromagnetic interactions influences our understanding of the basic physical phenomena in most fundamental areas of physics.

M: So after all, the experiment to see the change of the vacuum in quantum electrodynamics that we have discussed here is nothing but a prototype for phenomena occurring in other areas of physics.

R: Of course. This is a prototype not only for the world of elementary particles and elementary interactions, but it is as well a prototype for phenomena encountered in solid state physics and in many other circumstances where many particles interact.

M: Indeed the electronic structure of solids is very similar to the structure of the Dirac vacuum. One often has a band that is filled with electrons and one has states which are empty. A strong electrical field can excite an electron from the filled states to the empty states, and in this way create pairs of particles and holes which then will travel away in the electrical field and produce a current that, in turn, will produce useful electronic effects.

R: This well established phenomenon is commonly used today in semiconductor technology. However, it is basically different from the phenomena we have discussed in this chapter.

M: Because, of course, such a state is not empty of particles, but it is made of many particles. So it is not a vacuum state, but a many-particle state.

R: Yes, but of course one could equally well argue that our vacuum also contains particles, namely the source of electrical fields. However, this argument is not correct, because one can easily conceive (in a Gedanken experiment) a box to which an external electrical field of sufficient strength is applied. The empty space in the box is exposed to a very strong electrical field and will undergo the vacuum change that we have just discussed, so that 'nothing' actually acquires a structure when it is acted upon by some distant source. The colliding atomic nuclei are just a practical tool in our hands serving towards this purpose.

Practical Value of Fundamental Research

M: So, the difference between the physical phenomena seen in a solid and the responses of the vacuum exposed to the field of an atomic nuclei is, that in the latter case we investigate a change in the structure of the vacuum, of an 'empty' region of space, whereas in the former case it is a change in the structure of a real medium which is being looked at.

R: Well, while philosophically the vacuum appears of greater importance, the solid is today perhaps of larger practical relevance. But we know that fundamental understanding of physics normally predates applications by many years. Consequently it is of great importance that these questions about the vacuum be properly understood, so that at a later time applications can be forthcoming. Can we conceive of an application at all of the type of physics we have been discussing in this chapter?

M: No, even a single practical application of the formation of the charged vacuum is presently not at hand. But it is a typical circumstance in scientific research that one starts by investigating fundamental concepts, and then the proper understanding of these concepts leads to new problems and further research, and at some time, quite unpredictably, this can lead to applications which nobody could think of while carrying on with the fundamental research.

R: We carry out the research about the vacuum just because it is of crucial importance in our understanding of physical phenomena and physical laws, and not for reasons pertaining to a specific application.

M: But these applications will no doubt come.

R: Not necessarily tomorrow.

M: But maybe many years from now.

R: It is fitting here to take a look back about one hundred years and to remind ourselves what were the fundamental questions asked in physics at that time in order to appreciate in full how physics and our understanding of the world has changed.

M: A main topic of that period was concerned with the production electromagnetic waves.

R: And another one was the concern about the velocity of light being the maximum velocity.

M: Or with the question of what the elements are.

R: In other words, things which we apply daily by switching on lights in our kitchen...

M· ...or a radio or television set,..

R: ...or a microwave oven when we cook, or turning the ignition in our car to start the engine, or trying to use a laser to measure quantities or using a plastic bag to carry things. All this is only possible because of the studies in fundamental physics made about one hundred years ago. But perhaps the most important issue of all is the understanding of relativity, the foundations which were laid a hundred years ago.

M: The practical application of relativity in everyday life is still not very large, is it?

R: That is not quite true, as about 10 percent of all electrical energy today is derived from the relativistic effect of the conversion of mass to energy in nuclear fission. But more importantly, relativity has provided us the framework for understanding of fundamental issues of yesterday.

M: Well, so it is always good to remember that fundamental research eventually, inevitably, leads to application, though often it takes very long, even fifty years for them to materialize.

Chapter 4

The Opaque Vacuum

Light Propagation in Vacuum

R: Let us take a good look at light traveling through the vacuum. Berndt, would you think that light can be influenced by the diverse properties of the vacuum which we have discussed.

M: In the absence of other electromagnetic fields, a photon will travel freely through the vacuum. That is just how we define the velocity of light. We measure it as the speed by which light propagates in the vacuum surrounding us.

R: And we also determine that this velocity is independent of the frequency and wave length of light.

M: Right. We find that all photons propagate at the same velocity, which means that photons are massless. This is known to a very high degree of accuracy, because we can observe photons which come from distant stars many light years away.

R: So the fact that we have measured the velocity of light to have the value of about 300 000 kilometers per second includes all possible effects of the vacuum on its propagation.

M: Yes, but some of these effects, of course, mean that a photon can polarize the vacuum while it travels. All such effects are incorporated into our description of a photon.

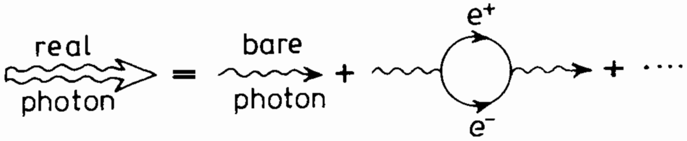


Fig. 4.1: The concept of a "real" photon which is being experimentally observed includes all the effects of the vacuum polarization.

R: Aha, while the uncertainty relation permits any photon to become an electron-positron pair for some time, and then to recombine and become a photon again, all this is already incorporated into the physical properties of the photon as we know it.

Two Beams of Light interact with each other!

M: Yes. But that makes it possible for a second photon to scatter from the first photon because if the second photon arrives when the first photon is just in a state of being an electron-positron pair it will see a charge distribution in the vacuum and will scatter from it.

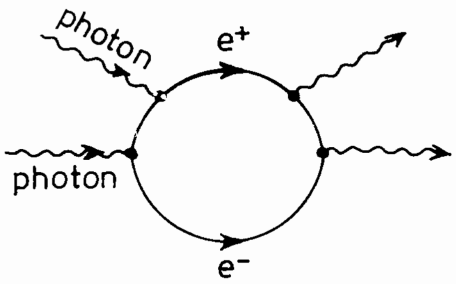


Fig. 4.2: Delbrück scattering: a photon can scatter on the vacuum polarization cloud produced by a second photon.

R: Thus a photon in the vacuum has a charge distribution, but maybe we should say it differently. A first photon polarizes the vacuum, and the second photon scatters from the polarization of the vacuum that the first photon induces locally, where it is at the time.

M: This is so, you see, because physics is always what one can measure, and if a single photon goes through the vacuum, one cannot measure that it spends part of its time as an electron-positron pair. Only if a second photon comes along, can one actually see that the first photon already has changed the polarization of the vacuum.

R: That effect must have been studied carefully. How does one perform an experiment to measure photon-photon scattering?

M: Well, the effect was theoretically predicted long ago, shortly after it was realized that the Dirac sea of electrons and positrons must be there. Heisenberg thought about it and Delbrück, who later became a pioneer in biochemistry, proposed an experiment at that time. But it is a very tiny effect, so still today the scattering of two laser beams on each other has not been observed.

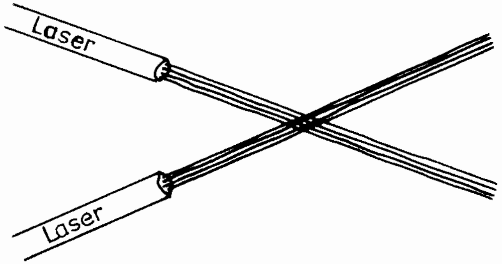


Fig. 4.3: Two intersecting laser beams experience an extremely weak scattering (Delbrück scattering) through the interaction of the photons with the vacuum polarization. The intensity of lasers available today is, however, insufficient to prove this effect experimentally.

R: What is the main cause of the difficulty?

M: The difficulty is the smallness of the charge distribution that the photon induces in the vacuum.

R: Could we perhaps improve the conditions by making laser beams extremely intense?

M: Yes. It is an effect that grows rapidly with the power of the laser field. If we were to have much more intense lasers than we do today, we could do an experiment and observe the effect.

Scattering of Light on the polarized Vacuum

R: That would be very exciting indeed. But in absence of sufficiently powerful lasers, we could of course imagine that we measure the polarizability of the vacuum induced by the electromagnetic field of a nucleus or a strong magnet by simply letting laser light pass through it.

M: That is true. This is the way that photon scattering from the vacuum has really been observed, namely by photon scattering from the vacuum polarization of the field of a heavy nucleus. Also experiments are in progress which try to observe the scattering of a photon from the vacuum polarization of a strong macroscopic magnetic field. Sucessfully measuring photon-photon scattering in such experiments would amount to observing the vacuum polarization of a macroscopic, extended electromagnetic field, for example of the field generated by a superconducting magnet.

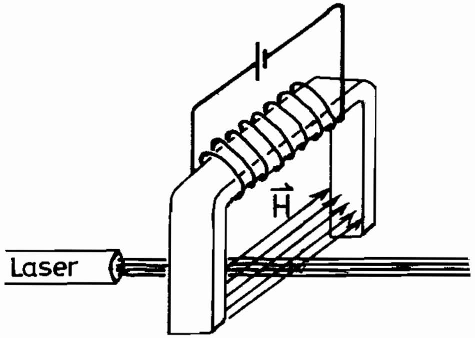


Fig. 4.4: Experiments to prove the Delbrück scattering of a laser beam on a strong magnetic field are in preparation. In the actual experimental arrangement the laser beam runs in the direction of the magnetic field lines.

R: These experiments are currently being prepared at CERN, and it is my hope that they will confirm our understanding of the vacuum.

Is there an Elementary Light-Light Interaction?

M: Now, the smallness of this effect obviously depends on the fact that photons do not interact directly with each other, but only indirectly, by polarizing the vacuum. Is it imaginable that photons could interact directly with each other?

R: Yes, in principle that is not unthinkable, if there could be more than one kind of photon.

M: What do you mean by more than one kind of photon? Do you mean that photons can have different polarizations, for example?

R: No, what I really mean is that electrons and positrons come with two different charges; there are particles and antiparticles. We would need photon-like particles that come in two different types, not particles and antiparticles, but particles with a new type of internal property other than just the polarization. Effectively this would be a new kind of charge.

M: This is something that I have always wondered about, and maybe you can tell me more. Why does the photon not have a charge, electrical charge or any new other charge?

R: Well, it is necessary that it have no charge, otherwise our vacuum would probably be very opaque. Let me explain what I mean: Even the extremely weak effect of photon-photon scattering which we have just discussed implies that there is some kind of a photon-photon interaction. Now what would happen if this interaction were attractive? Photons could cluster. Now, photons are bosons, that is, particles that like to be in the same state. Therefore, if there were to be some kind of attractive interaction between them, they would like to clump together.

M: But we know that photons attract each other, because photons have energy and energy gravitates, so photons can attract each other by their gravitation.

R: Well, that indeed is perhaps of great relevance for the cosmology of the universe, but to achieve substantial strength of gravity, an enormous number of photons must be put together into a big radiation clump. Formation of such a radiation clump is not easy. However, if the interaction would be substantially more attractive than that due to gravitation, it would perhaps be possible to already have photons clump in small microscopic objects.

M: Would perhaps ball-lightning be such an object?

R: That is a very interesting question. Of course, we both know that ball-lightning is not made of photons, but of ionized atoms. But the principle is exactly the same. The point is that if there would be a sufficiently strong attractive photon-photon interaction, then most of the photons made in the universe from its beginning would have clustered and clumped in the vacuum, and our vacuum would be extremely opaque.

M: All right. So let us assume that we have a different class of particles, which are similar to photons, but which have another kind of charge and attract each other. Then I would guess that they would form something like a solid. I mean, we know that electrons and ions together can form a metal.

Gluons: The "Photons" of Strong Interaction

R: Yes. Actually this is not just an assumption. We know today that there are particles very similar to photons, but subject to a very strong interaction. They also can travel at the velocity of light through an empty vacuum, however, due to their strong interactions they have already clumped together since a long time.

M: So what you mean to say is that the whole world is filled with a kind of solid or liquid made up of clumps of these particles?

R: That is very likely so. Actually this is believed to be the explanation of why the constituents of elementary particles, which we call quarks, cannot travel freely through the vacuum in which we live.

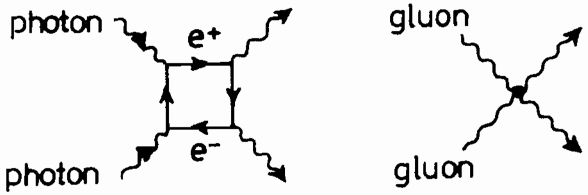


Fig. 4.5: Gluons, the "photons" of strong interaction, come in eight different varieties ("colours") that can directly interact with one another.

M: The particles which are similar to photons but attract each other and stick together are very appropriately called 'gluons'. Now tell me, Jan, why don't we normally see this sea of gluon clusters?

The Gluon Vacuum

R: Well, we don't see the gluonic structure of the vacuum because gluons interact neither with photons nor with electrons, because they are not electrically charged. They also do not interact with the constituents of atomic nuclei - protons and neutrons - although these are constructed from quarks which interact with gluons.

M: To give a simple example how it can be that nucleons don't interact with the gluon vacuum, consider an analogous situation of a bubble of air moving freely beneath water.

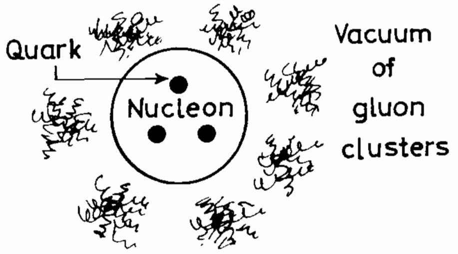


Fig. 4.6: Nucleons, i.e. protons and neutrons, are like bubbles in the vacuum made out of clumps of gluons. The building stones of the nucleons, the quarks, can only be found inside the bubble because the gluonic vacuum is opaque and impenetrable for them.

R: Yes. Of course, we know that such bubbles wouldn't move entirely freely, but if we were living in water which fills a large region of the universe, then bubbles of air could only be observed to either propagate almost freely or to coalesce to form larger bubbles. That is precisely how we today believe that atomic nuclei are formed out of individual nucleons. Think that each individual nucleon is like a bubble of air in water by analogy.

M: So atomic nuclei are nothing but clusters of bubbles.

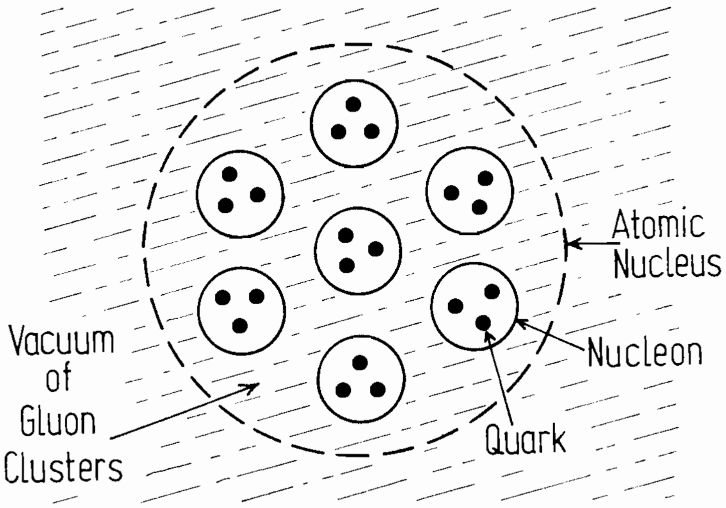


Fig. 4.7: An atomic nucleus in the language of modern physics is a collection of nucleon bubbles in the clumped gluonic vacuum.

R: Yes. Now, of course, for a big cluster called the nucleus to be created, there must be a certain kind of interaction between bubbles, and that is not a trivial matter at all. But each individual bubble, a nucleon, i.e. proton or neutron, is actually a freely moving object in the vacuum.

M: We were talking about gluons, we also talked about particles called quarks all along, but now we are talking about protons. We should explain what these have to do with quarks and gluons.

Structure of the Nucleon

R: Well, the bubble we called a proton has constituents within it -- like air in an ordinary bubble. And these constituents we call quarks. These quarks would very much like to be free and to travel individually through the vacuum. Unfortunately this vacuum is full of the "water" which we call gluons.

M: So quarks behave similarly to the air in underwater bubbles, which would like to expand or dissipate, except that the water pressure keeps it together.

R: Very much so. What is probably happening is that quarks try to get out of the bubbles all the time, but they scatter from the clumps of gluons in the surrounding condensed gluon vacuum, and are thus prohibited from becoming free and independent particles.

Vacuum Pressure

M: But there is something we must understand better. We said that around the bubbles is gluon vacuum, and to keep the bubble together it must exert some pressure on the bubble. How can a vacuum exert pressure?

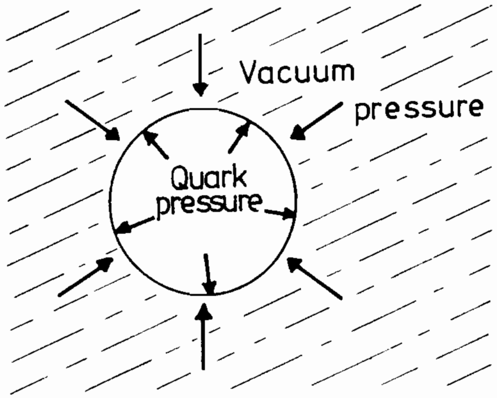


Fig. 4.8: The bubbles in which quarks are found are held together by the pressure of the gluon vacuum.

R: As we have just discussed in the example with water filling all space, the vacuum can certainly exert pressure if quarks interact with gluons. The situation is basically as follows: if we want air to expand into a larger space, it has to displace the water. But if that is not possible because all space is filled with water, then this water will act back on the air bubble and exercise pressure on it. At some early time in the evolution of the universe, it is quite likely that at the prevailing very high temperatures all the "water" was actually evaporated, and there was only vapour left. At that time quarks could move in a universe consisting of a 'vapour' of individual gluons and quarks, which today only exist as constituents of protons and neutrons.

The Casimir Effect

M: Now there actually is experimental proof that the vacuum can exert a pressure. It is called the Casimir effect. But this has to do with the vacuum of quantum electrodynamics and is not directly related to the vacuum of the strong interaction.

R: But it is a matter of principle and not one of detail. As we have already discussed in the last chapter, one has to establish a principle, and that principle arises from our understanding of the behaviour of a vacuum between, for example, two conducting plates.

M: Yes, under such conditions the Casimir effect arises because the quantum vacuum is not empty. There is always a certain probability that it contains particles or energy quanta. Now we know that in a vacuum between conducting plates, the energies of the states of these quanta will be different from those in a free vacuum.

R: Yes, that is the principle. If we put two parallel conducting plates like those of a capacitor into the empty space, then the kind of quanta which will appear for a short time and disappear again must satisfy the constraint that all electric fields on the surface of the conductor must vanish, because of the currents which are induced in the conductor.

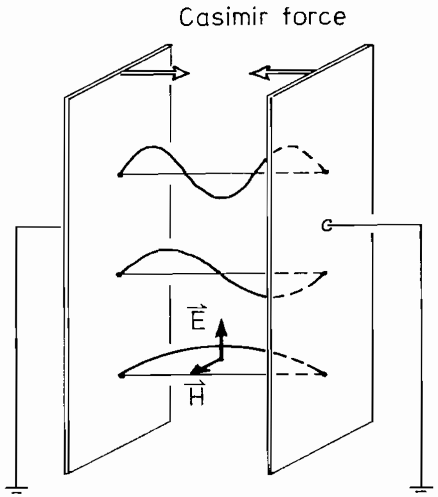


Fig. 4.9: The Casimir energy between two conductive plates has its origin in the dependence of the oscillation modes of the electromagnetic field on the distance between the plates.

M: This is analogous to the frequency in a resonator depending on the size and the shape of the resonator. Two conducting plates define the specific frequencies of electromagnetic waves which can be excited.

R: Alternatively, consider a string on which you can excite different tones and make music. Only certain pitches can be excited, and these depend on the length of the string. Exactly the same phenomenon occurs when you put two conducting plates face to face into the vacuum. We can then excite only virtual particles of certain discrete energies in the vacuum.

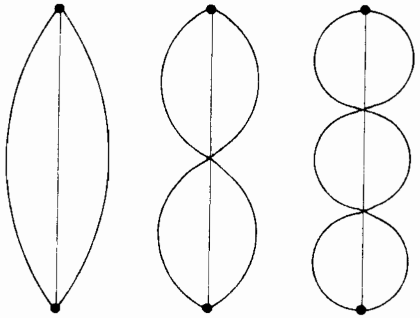


Fig. 4.10: The frequency of the resonating vibrations of a string is determined by the length of the string.

M: So the energy of these excitations depends on the distance between the plates, and if we sum over all these possible excitations, then we find that the energy of the vacuum must depend on the size of the separation between the two plates.

R: But not only the energy. What we would find is that since the energy now changes as we move the plates and so change the volume which is contained between the plates, there is a force, a pressure if one wishes to see it that way, which depends on the distance between the plates.

M: This force has actually been measured in experiments.

R: Yes, so one has really seen that a vacuum can act on a macroscopic object which modifies its properties. Even if it is only the boundary of the vacuum. This is what one calls the Casimir effect.

M: Yes. It was proposed almost forty years ago now. In historical perspective, it was perhaps the most important step towards today's understanding of the vacuum since Heisenberg's proposal about the scattering of light by light. But let us come back to the vacuum of the gluons. We now understand why the vacuum can exert a pressure on the quarks which depends on the size of the bags in which the quarks exist.

Vacuum Structure and Confinement of Quarks

R: Yes, indeed. We have to realize that the region in which the quarks can exist is free of the vacuum structure which, as we discussed, is probably some complicated gluon cluster state that repels the quarks. The confining constraints at the boundary will have the consequence that the energy states of virutal particles are changed, as in the Casimir effect, and consequently there is a pressure acting on the surface of this region. It turns out that this pressure is directed inwards. If we were to remove the quarks from such a region of space, then we would expect gluons to fall into this region and occupy it, as they have a natural tendency to be everywhere, i.e., we expect that the structured vacuum has a tendency to enter the region which is occupied by quarks.

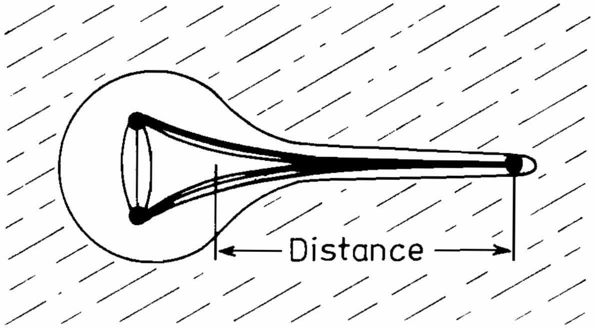


Fig. 4.11: The energy required to pull a quark out of the nucleon bubble increases in proportion with the distance. In order to completely isolate the quark an infinite amount of energy would be necessary.

M: What are the experimental proofs that this is correct? Certainly there must be some way to detect experimentally that it is the vacuum around the quarks which keeps them together and which does not allow quarks or gluons to propagate freely in it?

R: Well, I think the question should be inverted. The experiment shows that individual quarks are confined to the interiors of the elementary particles, and the question is asked: how can it be that we do not observe any single quark? Our present answer is: Because the vacuum is structured - in order to remove a quark which carries the strong interaction charge, this structure has to be displaced, and the displacement of the vacuum structure costs a lot of energy.

Are there Free Quarks?

M: How is it with free quarks? People have looked for free quarks in many, many experiments, and I even remember that somebody has claimed to have seen individual quarks.

R: Firstly let me say that in principle it is not impossible, in the kind of picture we have developed, to have a single quark. What is required is that the range of the glue interaction be finite, as is the case with the weak interaction that we will discuss in a later chapter. If that were the case, then even the clustered gluon vacuum would permit the existence of a very large region of space filled with only a single quark...

M: ...because the field around the quark extends only over a finite region and therefore can displace the structure of the vacuum only in a finite volume. So free quarks are possible only if the gluon range is finite. It is somewhat similar with the basic law of electrodynamics: If the inverse square law of a force between two particles would be attenuated, this would have grave consequences for the observed charge inside a sphere. If you make the sphere larger, the observed charge would be reduced by attenuation. The same is true here if the range of the gluon force is attenuated, then we can have single quarks, because only a finite amount of energy is necessary in order to disturb the structure of the vacuum. In order to test these possibilities it is certainly important to look whether one can find single quarks in nature. Most of these experiments really try to find a very special property that one assigns to quarks, namely that their charge is not the unit of the electron's charge.

R: Yes, it is indeed a special property, special in the sense that it is different from what we find looking at electrons and protons. But it is not special at all in the sense that charge differences between different quarks are always integer, which is a nice and theoretically a very much appreciated feature. However, yes, it is true that quarks have been looked for by observation of their electrical charge, and still today there are many experiments trying to find what is said to be a "free" quark. We should better here say not "free", but a <u>single</u> quark. These experiments may indeed one day succeed, but if they don't succeed, then the picture is actually much more beautiful and theoretically more internally consistent. This is so simply because the interactions between quarks so much resemble the interaction between electrically charged matter that one almost has the impression that they are of the same kind, that one could see a certain unification of the fundamental interactions emerging even at this early level.

The Vacuum determines the Properties of the Interaction

M: So the strongly interacting, opaque vacuum is a beautiful example of the principle we talked about in the beginning, namely that the laws of nature and the laws of physics have to be supplemented by a knowledge of the real vacuum state. As we have seen, the effective properties of interactions like the electromagnetic interaction or the gluon interaction depend on the vacuum state.Because the vacuum state of gluons is quite different from that of the electromagnetic interaction, the properties of this interaction are also quite different.

R: This is how the vacuum acts back on the physics of the things we look at. But this structured vacuum of what is commonly called "quantum chromodynamics", the quantum theory of interactions between quarks and gluons, really depends in an extreme sense on the understanding of the fundamental structure of the gluon vacuum, and it lives from it.

M: How well do we understand this structure today? I mean, do we really understand the details of the structure of this vacuum, or are they still to be discovered?

R: I think we know nothing really. We realize that because gluons are (colour) charged and because of the observed absence, or at least, the very likely absence of single quarks, the vacuum should be structured. On the other hand we have not been able to mathematically derive the properties of this structure and to understand the details of the new vacuum state starting from first principles. Now, that isn't too bad. The history of science shows many instances where this situation has occurred.

M: Can you give an example?

R: I am thinking for example about the theory of superconductivity. Superconductivity was actually discovered accidentally, as are many important phenomena, and it took some forty years, if my memory serves me right, to unravel the structure of this state. And indeed the physics that went into understanding it is in many respects similar to what we are discussing in the context of the strongly interacting vacuum.

M: But, of course, part of the reason was that superconductivity was discovered before quantum mechanics had been developed, and we know today that one needs quantum mechanics to understand superconductivity. So it was not really possible to understand it immediately.

R: While you tell me all this Berndt, I should remark that perhaps we don't have the theoretical means to understand the structure of the vacuum yet. We recognize that such a structure is necessary. Maybe we are just where Lorentz was when he proposed the contraction of moving objects, but it was Einstein who incorporated the Lorentz contraction into a more general theory of relativity and gave us a general understanding of the effect of length contraction. It is indeed possible that we have the ingredients of a proper description in our hands, but we are lacking the final conceptual and intellectual understanding to be able to present a holistic picture of the physical phenomenon of the vacuum.

M: Nowadays many scientists believe that computers are the solution to this problem. I mean, they think that all we need is a big supercomputer, and then we will be able to calculate every property concerning the vacuum. But that alone would not help our conceptual understanding at all. I think that it is in fact important, in order to support the qualitative ideas which we present here, to quantitatively perform a numerical simulation. This is not an experiment. It is a way to evaluate a numerical model in which the phenomena would occur in a way similar to that described here. But we gain no understanding by verifying that Lorentz's contraction is the contraction of individual atoms.

R: This is a very relevant point. If you have a rod and you move with a finite velocity, Lorentz observed that in order to explain certain experiments, it is sufficient to assume that the rod is contracted. Now that can, of course, be made much more fundamental by saying that the rod consists of individual atoms, and each atom is contracted in the direction of motion.

M: But we still have to understand why the atom contracts. When Einstein tried to understand how electrodynamics looks for a moving observer, he found quite unexpected results which, like the correlation between mass and energy, is at the foundation of our new concept of the vacuum.

R: But let me return to the original issue: by verifying with an elaborate calculation that the contraction of a rod can be taken back to what we understood as a contraction of each individual atom, we have gained no conceptual understanding of the contraction. The same with the vacuum. By verifying in a major numerical model that the glue - glue interaction is actually leading to the structured vacuum, we have not gained much. We don't know what kind of structure it is; we don't know about the properties of this vacuum beyond the fact that actually the structure has arisen. It is very important that such a quantitative understanding be achieved. But one should not overemphasize it. We are not going to unravel the secrets of the vacuum by showing that they are there.

Chapter 5

The Melted Vacuum

(Quark-Gluon Plasma)

Dissolution of the Vacuum Structure

R: Berndt, we have seen now that the vacuum has so many different structures. Can you think of an experiment in a laboratory which would make a global change in the structure of the vacuum of strong interactions?

M: Well, Jan, when we surveyed the vacuum and its possible implications for physics and our understanding of how the laws of nature work, we also discussed that maybe by accident we might trigger a global transition of the vacuum, which would be a catastrophic event. But what you think about now is certainly not such a global change of the vacuum of the whole universe, but rather a change of the vacuum on a scale that is large on the nuclear size, but still small on a macroscopic size.

R: When I say 'global', I mean 'global' on a microscopic scale. It must be large compared to the typical structural scale of the vacuum. In other words, if you think of a crystal, you must have an extended crystalline structure, and if you speak of a droplet of water, it must have a sufficient size such that the properties of the liquid dominate the properties of the surface. Of course you do not need to melt or vaporize all the water in all the oceans to understand the properties of water. But you would like to have a sufficient amount of it, a small droplet which is large enough for you to measure at what temperature water boils.

M: Now this is an experiment I like to think about because it is not so dangerous for us. When we discussed the structure of the strongly interacting vacuum, we already found that the vacuum of the strong interaction comes in two different forms. The one was the vacuum which is everywhere, probably consisting of a complicated soup of interacting gluons which confine the quarks, and the other is the one that is found inside elementary particles, inside the protons, for example. And we also said that if one looks at a nucleus with a magnifying glass, it would probably look something like an assembly of bubbles in water, each bubble being like...

R: ...a hole in Swiss cheese.

Compressed Nuclear Matter

M: Right, the nucleus would resemble Swiss cheese. Therefore what one can think about would be to simply compress a nucleus, compress it so much that the bubbles, the holes in Swiss cheese, start to overlap, and finally form one huge bubble.

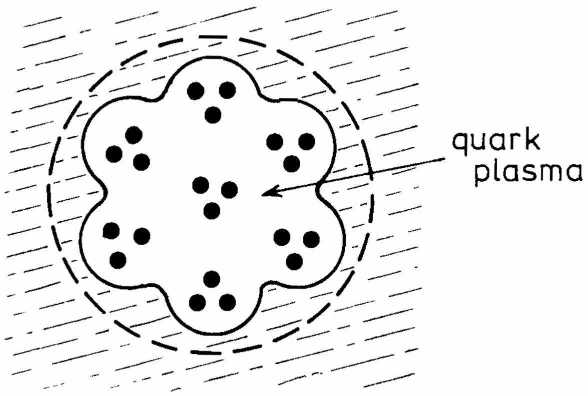


Fig. 5.1: If one could compress an atomic nucleus hard enough, the individual bubbles would fuse into one single giant bubble in which the quarks can move freely.

R: Is such a classical picture correct when one tries to understand properties of compressed nuclei?

M: Well, probably this picture is too simplified, but we do not understand too well anyway how the nucleus is actually built up of quarks and gluons, so maybe such a classical picture is not so bad after all as a starting point.

R: It is hard to say, but we realize that the path to an extended local change of the vacuum is in compressing the nuclei. You mention that this other vacuum which was inside the protons has a second structure. What kind of structure is this?

M: We have good reasons to believe that it is similar to the dielectric vacuum of electrodynamics, that particles which have a strong charge such as quarks or gluons can move almost freely in it, but are confined by the normal vacuum which is everywhere else.

R: If one thinks of the quarks and gluons floating around, then what we have is a real empty space, don't we?

M: Yes, the inside of the bubbles is very much like our imagination of empty space filled with well-defined particles. But let me come back to the experiment. Now compressing a nucleus is certainly not an easy thing...

How Can One Compress Atomic Nuclei?

R: What kind of a press would you use?

M: This is precisely the point. We cannot put a hammer on it, but what one might do is to bang two nuclei into each other.

R: That is certainly not going to work. You are not going to tell me that if I take two billiard balls and scatter them from each other, that I will compress them.

M: Now I would certainly not want to tell you that. But think of two cars. When you bang two cars into each other, they would certainly be compressed and stay compressed.

R: Yes, but that would be just the opposite of what you want to achieve. If you view the inside of a car as the empty bubble and the outside as the structured vacuum, you actually are not making larger bubbles, but you are making bubbles that are smaller.

M: Well, you are really making life for me as an experimental physicist difficult. But let me take another example. Let me think about a sponge soaked with water which fills up all the empty holes in it. Now you compress it by hand. What would happen is that the water would flow out of it and what you are left with in the compressed state is simply sponge matter. The same thing will happen if you take the sponge and fling it wildly against a wall. By its own inertia it will be compressed when it hits the wall, and the water will flow out, and for a short time the sponge will be compressed. Of course, it will not remain in a compressed state for very long, but if we can take a snapshot at the right moment, we will see a completely compressed sponge.

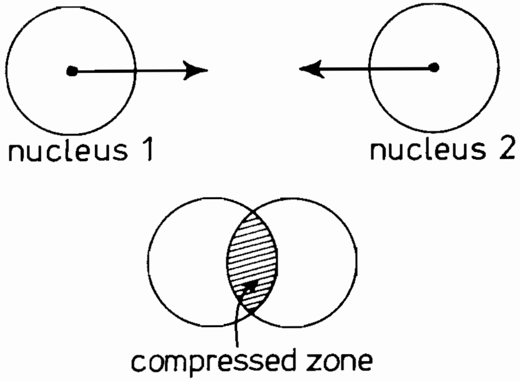


Fig. 5.2: In the collision between two atomic nuclei accelerated to high energy of a high density zone develops in the region where the two nuclei overlap.

R: But actually the experiment we want to do is to throw two sponges at each other in water.

M: Precisely. So we should take this as a warning that the experiment may not be easy. But one could certainly try it. What do you think, Jan?

Nucleus-Nucleus Collisions

R: I don't think it is only going to be an attempt, it is going to be an experiment that will succeed. But what we see in this discussion is that it will not be an experiment that you can do in your backyard. You will have to use very powerful accelerators and sophisticated experimental techniques. And it is not to be expected that all nuclear collisions will lead to the new form of vacuum. It is clear from our discussion, I guess, that it is more likely that many other things will happen as well. But sometimes the giant bubble of empty 'perturbative' vacuum we want to look for will be formed.

M: Now fortunately these very powerful accelerators already exist, and they may be used for such experiments in the near future. It is also fortunate that there are some very courageous physicists around who actually plan to do these experiments. But now, let us see what would be the properties of this vacuum when we could establish it in such violent nuclear collisions. How would we describe its properties?

R: Certainly if we think of a sponge, we would have to know how much sponge there is per unit of volume, right? That would be the density of quarks in the perturbative region of vacuum.

M: How much energy do you think we would need to make it?

Latent Heat of Melting the Gluon Vacuum

R You mean how much 'latent' heat is required to actually go from one vacuum to another when we melt the gluonic structures of the true vacuum?

M Yes. Can we make an estimate of this quantity?

R Yes, it is quite an easy task. Everything in elementary particle physics comes in units of a proton mass, 1 GeV. And every volume comes in the unit of a cube with one edge of the same length as the radius of the proton, so why don't we say one mass of a proton per one cubic Fermi, one GeV per cubic Fermi. This turns out to be as good as the estimate that one can make with very sophisticated calculations.

M And of course one will do these complex experiments to find out more precisely the latent heat of the vacuum.

R Yes. Of course, after the experiment all the theoretists will say that they knew in advance what the latent heat of the vacuum had to be. But I think that today we have only very vague ideas about the precise number, and probably any figure that is between five times smaller than one GeV and five times larger than one GeV has been mentioned in publications. But there will be somebody who is right. Consequently, there will be some happy man after the experiment who will stand up to claim that his prediction was correct.

Difficulties in Predicting the Physical Properties of Complex Materials

M: So we have here a situation which is very different from the one, for example, in the experiment on muonic helium, where one had a very precise prediction of an effect, which was later confirmed by measurement.

R: Yes. Actually there are many reasons for this, I think. But the most important one probably is that we believe we have the right theory, but we are unable to compute within its framework the properties of matter. That reminds me, of course, that muonic helium is a very simple system, and that we can compute almost everything there. But if I were to ask you to compute, starting from the basic principles of quantum electrodynamics, the properties of the sofa on which you sit, including its apparent colour, strength and surface brightness, I think you would be working for years on the problem, don't you agree?

M: I would probably avoid sitting on a sofa under such circumstances. But I think we owe it to our readers to tell them about the properties which this new excited state of the strongly interacting vacuum has.

Hot Nuclear Matter = Quark-Gluon Plasma

R: Yes, we should begin by summarizing again what is really happening. We take two large atomic nuclei, and we bring them together at a sufficiently high speed so that the individual nucleons cannot move away from the collision zone when these nuclei collide. Therefore a compression of the nuclei will follow, and this compression will bring the individual nucleons much closer together than they otherwise would be in an individual nucleus. When they are very close together and even overlap, we can view their interior as being one large bubble. This bubble is filled with the different quarks which, of course, are brought in by the nucleons of the incoming nucleus. However, these quarks will no longer be in the lowest state which is permitted to them by physical laws .

M: Because if you compress something suddenly, you cannot avoid heating it up.

R: Yes, that is exactly the point. We thus find in this large bubble of, as we called it, perturbative vacuum, a high density of quarks at a certain finite temperature. Therefore we have two different quantities which will describe the state of our perturbative vacuum. We have the inside density of quarks and the temperature.

M: I know very well how to calculate the properties of such a hot gas of free particles. Such systems have been studied in physics over and over again.

R: It is true that this is a very well studied problem in principle. However, a new element now is that these particles have a special charge, called colour charge, which is the origin of the strong interactions in the first place. This charge doesn't disappear when the particles are found in this big bubble of excited vacuum, though the resulting interactions are in certain circumstances modest. But they are still relatively strong. So we must expect that this kind of a gas is more like a liquid, or maybe it could even become a solid, if not too much excited internally. Doubtlessly it is a very nonideal gas.

M: Now the whole scenario that we are developing here, namely that we have a region of space which is large on a microscopic scale, which is filled with particles that have a high temperature and which have a charge, is very similar to the electron-ion plasma formed when atoms dissociate into electrons and ions at high temperature or high density. Would you agree that this would be a reasonable description of the properties of the state?

R: Yes indeed. I do agree, but with a qualification. In regular plasma we consider two different carriers of charge: the light electrons carry a negative charge and the heavy ions carry a positive charge. The amounts of both must be the same in order for the plasma to be neutral, and, as everybody knows, such electron-ion plasmas are used for thermonuclear fusion. However, in our quark-gluon plasma, which we want to create in nuclear collisions, all the carriers of strong 'colour' charge have a similar mass, perhaps even a zero mass. As consequence this plasma is more homogeneous, and the components will be more closely coupled and will come to equilibrium much more easily.

How Can One Observe the Quark-Gluon Plasma?

M: But unfortunately the collisions between nuclei will proceed so fast that the region of space which has been converted into what we call quark-gluon plasma will not only be small but also short lived, making it difficult for us to stick some kind of thermometer into it. So we have to think about how one can observe the properties of the melted vacuum.

R: But do you really put a thermometer into the sun to find its temperature?

M: No, I measure the energy of photons which are arriving, that is, measure the wave length of the light which I see, in order to determine the temperature of the solar surface. And I can do the same in a nuclear collision except that the concept of surface now includes also time: we observe particles emitted by a surface at the end of the lifetime of the plasma. But if I want to measure the temperature of the interior of the quark gluon plasma, I have a greater problem, don't I?

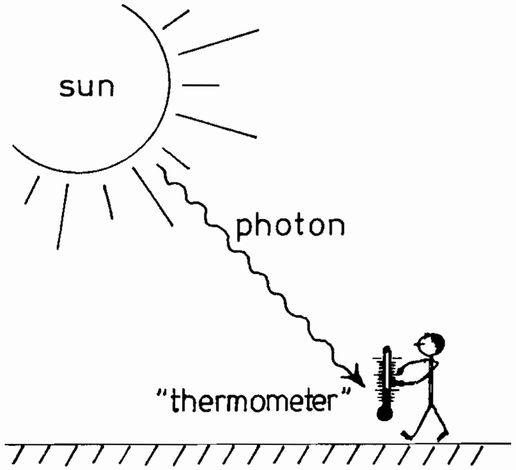


Fig. 5.3: The temperature at the surface of the sun can be measured by observing the sunlight far away.

R: We must look for particles which can leave the plasma volume without much interaction.

M: What kind of particles could it be?

R: I think, Berndt, you have to realize that we are talking of a variety of different particles. Some are almost noninteracting and penetrating, but then they are usually very difficult to produce in the first place. Others are easily produced, but then they also interact strongly and are reabsorbed. The best bet is on those which are in between: during the lifetime of the plasma only a few will be produced, but they can get out of the plasma and reach our detectors.

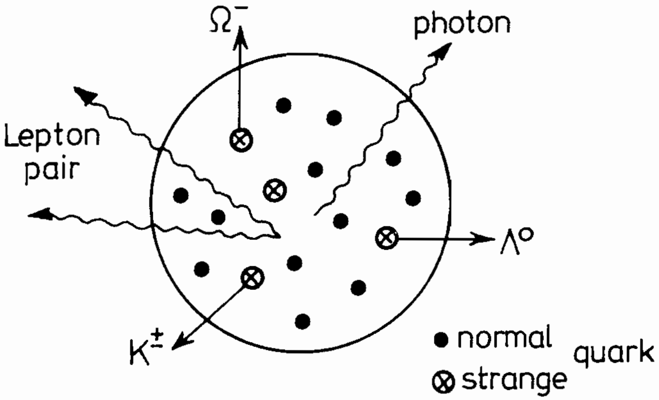


Fig. 5.4: The states inside the quark gluon plasma can be studied by means of suitable elementary particles which can leave the plasma unrestrained.

M: So what you really mean, Jan, is that we need particles which interact fairly strongly but not too strongly.

R: Yes, and which actually need to be <u>made</u> in the new phase which we create in nuclear collisions.

Strange Quarks: A Signal from the Quark-Gluon Plasma

M: So that there can be a real signal for the establishment of the new phase. Now, fortunately, quarks which we want to detect come in several species, and some of these species do not exist in normal nuclear matter. It was discovered many years ago that there is a third, fairly common kind of quark, the 'strange' quark, which can be easily created in collisions of elementary particles. The mass of these strange quarks is quite comparable to the typical energies of quarks in what we have considered to be the quark-gluon plasma. So when quarks or gluons in this plasma collide, they will certainly produce strange quarks.

R: Yes, and of course, the speed at which these quarks will be produced is well determined by the known strength of interaction between gluons and these strange quarks. So we can compute the rate of production of such strange quarks in the quark-gluon plasma.

M: And we can also compute how far they will travel without further interactions in the plasma.

R: Yes. Actually we don't think that they will travel very far without interaction. But they will not be easily absorbed again. They will not disappear once they have been created. The essential point is that they can reach the observer after the plasma cools down or dissociates, although not individually, but built

into other particles, such as for example (see Fig. 5.4), kaons ($K^{\pm}$), lambdas (Λ^{0}) or omegas ($\bar{\Omega}$).

M: Now before we really decide that strange particles are a good signal to look for as evidence for the formation of the quark-gluon plasma, we should consider whether the typical time scale for their creation is short enough so that they will actually be produced during the lifetime of the plasma. I think that these experiments are very expensive, and one should not try to do the wrong experiment in the first place.

R: I agree with you in this respect, and one could argue very convincingly that, given the fact that these particles have a mass which is about one fifth of the proton mass, their characteristic lifetime for production must be something of the order of the radius of the proton, for that is the time which light needs to travel through the proton. Actually, that is what we have found in a specific calculation. So we really believe that if we collide nuclei with many nucleons, there will be many of these strange quarks made. And what is also extremely important for the purposes of experimental observation of the new melted vacuum, there will be associated antiparticles containing strange antiquarks.

M: Now, do we actually understand why these particles, when they are created, will not decay before they come out of the plasma?

R: Yes. Normally, when we have a lot of time, strange elementary particles decay by a natural radioactivity similar to the radioactive decay of nuclei or the radioactive decay of the muon described previously. However, there are other forms of decay. In particular, it could be that the strange quark meets a strange antiquark in the plasma. And then the balance of strangeness can be depleted by particle-antiparticle annihilation.

M: Which would be just the reverse process of the strangeness formation reaction.

R: Yes. And that explains why we wanted some particles which are produced slowly. Then they also will be annihilated slowly, and in particular, one finds that the hotter the plasma, the easier it is to produce strange quarks, and as the plasma expands and cools with time, it is more difficult to recombine them again.

M: Now there is one thing which worries me a bit. We know that quarks also exist in protons and neutrons which form normal nuclei. When these nuclei collide without being converted into a quark-gluon plasma, but just stay nuclear matter, then you will surely also form strange particles.

R: I agree with you entirely. But consider for example strange antimatter. Normally antimatter is difficult to make. However, here we have the very special conditions of the quark plasma. We are producing with each strange

quark also an antiquark which is antimatter. What we can expect is that these strange antiquarks will coalesce to form, under favourable circumstances, strange antimatter, really antimatter with strange antiquarks built into it. The point is that we cannot expect large amounts of such matter to be generated in normal nuclear collisions, if dissociation to the new vacuum has not occurred in the collision. One could now contine to argue that this observation points the way to still another signal for the plasma. Why don't we observe just any type of antimatter? The point is that strange antimatter has a better chance of surviving the break-up of the quark-gluon plasma.

M: Also, strange quarks and strange antiquarks are mainly produced by gluons, which are not so abundant in normal nuclei and thus strangeness is an indirect evidence for the presence of gluons in the plasma.

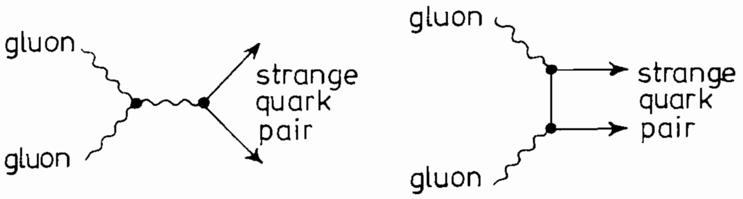


Fig. 5.5: Strange quarks are produced mainly by the gluons which are not present in ordinary nuclear matter.

R: Yes, that is very correct. The abundance of strangeness in the quark-gluon plasma is higher by a large factor than if the same collision had occurred without the phase transition. In a detailed study one finds that this is due to the gluons which are not present in normal matter. So one could, of course, study only the abundance of strange particles in order to establish the existence of the plasma.

Formation of Quark-Gluon Plasma by Cosmic Radiation

M: When we discussed the possibility that we sit in the wrong vacuum in the universe, we said that there is no danger at present, because there is always cosmic radiation around us which has tested previously the stability of our vacuum. Part of this cosmic radiation consists of a very energetic heavy nuclei. Isn't nature making quark-gluon plasma every day by cosmic radiation impinging on earth?

R: Very likely so, I wouldn't be surprised if there is quark-gluon plasma being made within viewing distance right now.

M: So why do we have to do complex experiments?

R: Because we must produce quark-gluon plasma where the special detectors are in order to learn about the properties of the melted vacuum.

M: You mean under controlled conditions.

R: Yes. Of course, you can put up a detector anywhere in space. If you wait for many years, there will be a very nice quark-gluon plasma event which you can observe. But then you will wait for a very long time before a second such event occurs. The reason is that while there are lots of cosmic particles, they can differ in their nuclear size, in their energy, in the angle at which they enter the experiment. The conditions are completely uncontrollable when one looks at cosmic rays. Nonetheless, there have been great efforts in recent years to do just such experiments. And I must commend the experimental effort. It has borne a lot of fruit. Today we may even say the quark-gluon plasma has already been discovered. There are very weird cosmic ray events which one could interpret as quark-gluon plasma events. However, due to the difficulties in doing experiments with cosmic rays, one has concentrated on easier types of measurements than for example observation of strange particles. Consequently, we don't have an unambiguous signal for quark-gluon plasma formation in cosmic ray events as yet. And very likely such evidence will only be obtained by carrying out accelerator experiments.

Cost of the Search for Quark Gluon-Plasma

M: Tell me, will these experiments be among the most expensive experiments which are done today, or are they comparatively cheap?

R: I think to name a price tag for fundamental physics is intrinsically wrong, and furthermore it is very difficult to estimate which are the direct and indirect costs associated with any single project. Even the expense of purchasing this book could be put into the basket of the cost associated with fundamental research. But to answer your question clearly and squarely, these experiments will certainly belong to the more costly ones. Although the machinery, the accelerators and some of the detectors are already in place, in terms of effort and human resources this work will be expensive. Quark plasma experiments will certainly compete in cost with most of the forefront experiments in physics.

M: Certainly the most expensive experiments will be those which do not look for strangeness, but look for other particles that may be a signature for the quark-gluon plasma, namely electromagnetically interacting particles like electrons, muons and photons, because these are not produced so abundantly, and one has to look for very, very small production probabilities.

R: Indeed, I agree with you. But these experiments also must be done, because the observation of these particles will be an essential cornerstone in our understanding of the quark-gluon plasma. And certainly there will be other experiments which we haven't discussed here which will be done and will open completely new opportunities for further study of the properties of the vacuum, once the initial investigative phase has been completed.

Is there Quark-Gluon Plasma inside Stars?

M: Once these experiments have been carried out and we have arrived at a better understanding of the transition between normal nuclear matter and quark matter, which is accompanied by a change in the strongly interacting vacuum, then we can probably better understand the structure of the very dense, compact stars which are called neutron stars. They are really nothing but giant nuclei having a radius of several kilometers.

R: Yes, as soon as quarks were invented, or very soon thereafter, it was realized that the interiors of these neutron stars could consist of quark matter. And the structure of the interior of these stars influence the theoretical work and understanding of the basic properties of these stars, such as mass, radius, and brightness.

M: Certainly this type of quark matter would differ from the one that is produced in collisions of nuclei, in that it is essentially cold.

R: I'm not sure. I really don't know. I have been worrying about this question very much. Today we believe that in a neutron star there is no further source of energy once the nuclear fuel supply has burnt out and that after the gravitational collapse it becomes de facto one large nucleus. But this presupposes that here will be no further source of energy in such stars.

M: You are really thinking that the energy residing in the mass of the nucleus might become abailable and converted into heat?

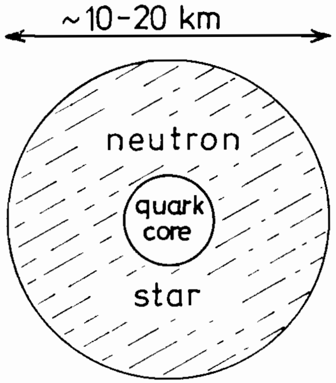


Fig. 5.6: Neutron stars form the final stage of large stars that have burnt out their thermonuclear fuel supplies. They have a diameter of 10 to 20 kilometers and represent nothing but an oversized atomic nucleus. In their center they might contain a core of quark matter.

Strange Objects in the Sky

R: Yes, indeed. We will have to discuss this in more detail in the next chapter, but just vaguely speaking, why shouldn't the energy contained in the rest mass of atoms and nuclei be burnt up into radiation in the dense centres of neutron stars? It could well be. We cannot exclude this possibility. There are very puzzling objects in the sky called quasars, and there are many things in the centre of galaxies that we do not understand. Extreme amounts of thermal energy are constantly being set free in these objects.

M: Black holes have often been invoked to understand such strange objects in the universe.

R: Black holes are a completely different subject, and I wouldn't want to touch on it now. We will come to it later. But here we note that that there must be sources of energy in the universe which go beyond what we know about nuclear fission and nuclear fusion. Now, these sources of energy could be connected to the burning of the rest mass of all matter or even as you have mentioned the energy could be won from a gravitational collapse, nobody today knows anything about it. Thus we do not know if really the centers of neutron stars are as cold as we believe them to be.

Burning of Matter in the Quark-Gluon Plasma?

M: But you don't want to say that producing quark-gluon plasma in high energy nuclear collisions might eventually become a very efficient source of energy?

R: I wouldn't exclude even that suggestion. Such applications can often arise quite unexpectedly. What I really can say is that everybody believes that matter was formed in an already distant universe. So we might find a way to destroy matter, to convert it to radiation and energy again.

M: And many physicists are speculating today about possibilities to do that.

R: Sure. We do not know at what stage your knowledge this opportunity will arise and if it will be practical. Today we have certain vague ideas only. If one is extremely optimistic one could already claim that the solution to this problem is around the corner, that the quark-gluon plasma provides it. I wouldn't bet more that 1:100 on this. But I would be prepared to put up one rand against your hundred, if you wish to bet against it.

M: I don't.

Chapter 6

The Grand Vacuum

Burning of Matter: The Ultimate Source of Energy

M: Now, Jan, you mentioned that it might be possible that the energy which is contained in protons and neutrons which form atomic nuclei may actually be converted into useful energy.

R: This is the dream of every science fiction author and I guess of many of the readers of this book. If you had a practical way to convert matter into radiation, into energy, we could travel to the stars. Yes, I do believe that this is possible, and what makes me believe this is the fact that we only observe matter in the universe. No antimatter has ever been seen.

M. Yes, although very extensive searches have been performed to find the signals for the presence of antimatter and possible annihilation of matter and antimatter in the universe, nothing of that sort has ever been seen.

R: Yes, but what this has to do with your question is: Sometime, somewhere in the universe matter has been made without antimatter. Or that antimatter is already around us and we just don't recognize it as antimatter.

M: Or that matter and antimatter originally were equally abundant, but somehow antimatter has been destroyed or converted into matter. As there is far more radiation in the universe than matter, and we know that in the early universe a considerable fraction of this radiation must have existed in the form of equal amounts of matter and anitmatter, the asymmetry between matter and antimatter is very likely not so great as it seems, at least as far as the underlying mechanism for it is concerned.

R: Yes, certainly. In any event this means that there is an asymmetry between matter and antimatter which developed since the universe was born. Now if we could gain control of how such asymmetry develops in time, we could convert matter into radiation.

M: In a sense we then would run the evolution of the universe backwards at an accelerated, controlled pace: maybe not in the whole universe but in a small reactor on earth.

R: That is the principle I am thinking of. Since the universe is so asymmetric, there must be a means of actually converting matter into energy, as energy once was the source of matter.

Can the Proton disintegrate?

M: What keeps us at present from using the energy that is contained in the proton and the neutron is that the proton is a very stable form of matter. It does not decay, thereby releasing its energy. We only know that the proton lives on the average for much longer than the age of the universe. But we know this only to be true in our vacuum, which developed during the expansion and the cooling of the universe, and it certainly is possible that the proton would not be stable in a different vacuum.

R: What this requires is that what we called the perturbative vacuum in which quarks reside is perhaps something which again comes in different shades and colours. What we really would want to do is to remove or destroy the quarks which make up the proton. If there were no quarks we would gain the energy, the latent heat, which resides in the melted vacuum which is inside a proton. But to be able to gain this energy we must rid ourselves of the three quarks which are inside the protons. Now these quarks would have to decay. What do we know about the decay of quarks?

M: Well, we know several species of quarks which can decay, such as strange quarks which we have reviewed before. When they decay, they decay into other quarks and give up some of their mass to form electrons, muons and neutrinos.

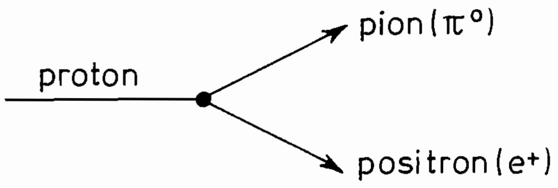


Fig. 6.1: One possible decay mechanism for the proton. Although in recent time such disintegration processes have been searched for with great effort, no such decay has yet been found. From this we can conclude that a proton under normal conditions remains stable on the average for longer than 10^{31} years (compare to the age of the universe now believed to be approximately 10^{10} years).

An Unexplained Symmetry of Elementary Particles

R: So, as these decays show, there is actually a relationship between quarks and electrons?

M: Yes, indeed. There is a very profound relationship. Actually we think today that quarks and leptons (i.e. electrons, neutrinos, muons) always come in pairs. For every kind of quark there is also one species of electron.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \dots$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \dots$$

Fig. 6.2: The known species of quarks known to us can be divided in pairs into groups ("families"). Each family of quarks corresponds to a family of leptons, i.e. particles related to the electron.

R: But do we understand why it is so?

M: Not at all. Although there are some theoretical arguments why it would be very nice if it were so, I think there is no deeper reason that we know of why the epton-quark symmetry is found.

R: Is it perhaps just an accident? What are the chances that this observation actually has some significant meaning?

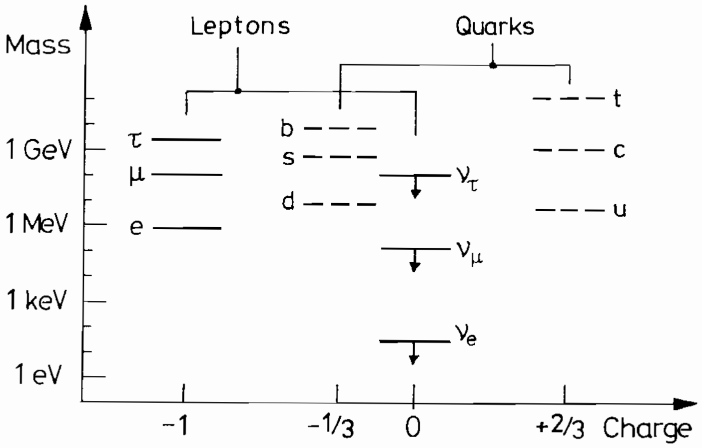


Fig. 6.3: Quarks and leptons can be ordered in such a way that they differ by one unit of charge each as shown here horizontally. Vertically their mass is shown - each mark on the scale denotes one order of magnitude.

Do Quarks have a Substructure?

M: It would be very surprising if it were an accident. Take for example the charges of quarks and electrons. We know that charges of quarks can be +2/3 or -1/3 of one elementary charge, so that they can differ just by one electron charge. And the charges of leptons, like electrons and neutrinos, the latter one being neutral, also differ by one unit of the electron charge. It would be very surprising if this fact that the difference in the charges is the same for quarks and electrons would be accidental.

R: Yes, I tend to agree with you. I further recall that the sum of the charges of all quarks and leptons is the same, a fact very necessary for diverse theoretical considerations. So actually one would like to view quarks and leptons as being a reflection of a certain substructure which resides in them. But if this is so, then this may again be related to the asymmetry between matter and antimatter in the universe.

M: Yes it may actually be that once we learn how to probe the substructure of quarks and leptons, we can also understand how it may be possible to convert quarks into leptons.

R: Do you want to say that a quark could annihilate with an electron?

M: In principle, yes.

R: That, of course, would be very interesting. That would mean that an atom could undergo a radiative decay and desintegrate into photons.

M: This has never been observed, as we have said, but it could happen even in our present vacuum on a very, very small scale. But it also may be that the structure of the vacuum forbids this process to occur. You know, when quarks and electrons are built from more fundamental particles, from constituents, there must be some interaction which binds these constituent particles together. Then it may be that the decay of the proton becomes possible only in a different vacuum state. In this case protons would be stable under present conditions.

The Unified Vacuum of all Microscopic Interactions

R: Maybe we again have the same picture which we had with quarks being constituents of the protons, that inside quarks there is a new kind of vacuum to be found.

M: That might just be the case. On the other hand it may be that nature has chosen a quite different and surprising solution. But in any case, whatever will be the nature of this substructure, a further vacuum state will be very likely associated with it.

R: Yes, that is really telling us that we should perhaps take a very good, close look at atoms. Maybe we should try to see if an atom can suddenly convert itself into radiation. We have already discussed muonic atoms. Now there we have for quite some time quarks and leptons very close to each other. And if they are close to each other, why then should they not annihilate each other?

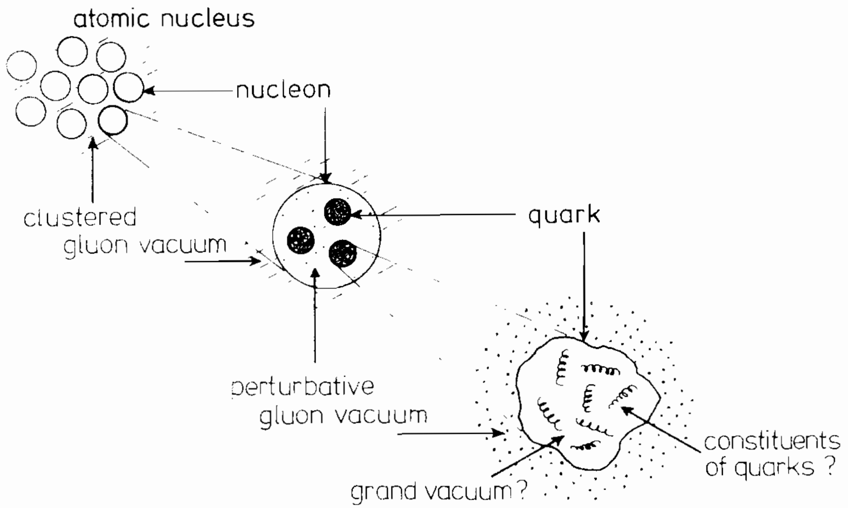


Fig. 6.4: It is assumed today that the quarks also have an inner structure which is determined by the vacuum of the unified interaction. The structural principle of the nucleons built out of quarks would then repeat itself at a lower level.

M: Jan, this process is quite unlikely, although it is by no means ruled out. I don't think muonic atoms are the right place to look for quark-lepton annihilations. But, what we can expect is that if we want to probe such new processes, then we will probably have to go to much higher energies than we can today. Now, since we don't yet have accelerators to carry out such experiments, one might on the other hand ask whether there are particles occurring in nature which carry the united vacuum on a relatively large scale with them and thus could stimulate the various reactions.

R: Do you mean a kind of a catalyst?

Magnetic Monopoles: Catalysts of Proton Decay?

M: I really mean a catalyst for the conversion of nuclear matter into radiation. And it has been speculated recently that monopoles may be such a catalyst.

R: You refer here, of course, to magnetic monopoles. Are those magnetic monopoles not the origin of the earth's permanent magnetic field?

M: No, very likely not. As we know, magnets on earth derive from magnetic dipoles with a north and south pole. It is not possible to separate these poles. But Dirac, shortly after he invented the positron, speculated about the possibility that magnetic charges also come alone, and these particles would have very funny properties. For example, if one magnetic monopole in the universe would exist, then we would understand why all electrical charge comes in multiples of one fundamental electrical charge.

R: Yes, I recall this. It was a very beautiful idea. What is really found is that the product of an electric and magnetic charge must assume certain discrete values in order for the laws of physics to have a very clear, reproducible meaning.

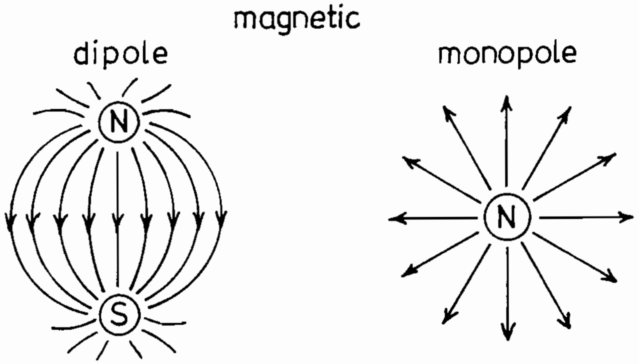


Fig. 6.5: All magnets on earth have the form of dipoles where the North and South poles cannot be separated. A magnetic monopole has not yet been found, its properties, however, would be most interesting. The magnetic monopoles probably carry a large region of the vacuum of the unified interaction with it.

M: In recent years we have started to understand that monopoles actually may not be pointlike. They may have an internal charge and they may carry with them part of a different vacuum, which belongs to the interaction that possibly connects quarks and leptons.

R: And they carry with them this vacuum which comes from the early stages of the universe, much the same way the charged vacuum in heavy ion collisions is carried locally by the atomic nuclei.

Search for Magnetic Monopoles

M: Magnetic poles are expected to be very massive, so heavy that we have no prospect of making them with accelerators in the foreseeable future. But they might have been produced in the early universe, when there was plenty of energy around.

R: But the point is that, of course, the universe is very large now, and if there were only few monopoles made in the beginning, we can wait for a long time before we find one. But what worries me even more is the fact that, as you said, they would be very heavy.If they are very heavy and they interact strongly, then it is likely that they sit in the middle of stars or galaxies...

M: Or in the middle of the earth.

R: Yes. They would just fall right through the surface of the earth to the middle of it. And that is precisely what I meant previously when I said maybe in the centres of galaxies, stars or planets there is another source of energy. Perhaps those magnetic monopoles sit in the centres of neutron stars, and whenever they encounter a quark, energy is set free.

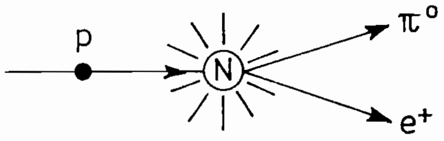


Fig. 6.6: A magnetic pole would greatly increase the decay of protons, thus working like a catalyst.

Energy Production with Magnetic Monopoles?

M: This would not be a particle decay, it would be more like a reaction process in which a quark is converted into electrons.

R: A reaction similar to a nuclear reaction, like nuclear fusion or nuclear fission perhaps?

M: It would be a reaction process in the same sense, and as we know that energy can be released in nuclear reaction processes, we can also expect that energy will be released in a reaction transforming quarks into leptons.

R: But if we firmly believe that quarks can be transformed into leptons, then the energy released will just be the difference between the masses of these particles.

M: We can calculate this from conservation principles, but something that one has to realize in that regard is that at the moment we really do not understand where from the masses of fundamental particles arise.

R: And similarly we do not have a theory to compute the reaction rates in this new unified vacuum of quarks and leptons.

M: We do not have an established theory. There are several theoretical models on the market, but at the moment we have no idea whether the proposed theories are correct or not.

R: So the way to find out whether our ideas are correct is to actually discover the process which could carry our spaceships to the distant stars.

M: That is, to look for the decay of protons or to find a decay catalyst such as the proposed magnetic monopole.

R: It might be quite futile if we just simply look at a piece of matter and wait for a decay of a proton or the passage of a monopole through it. Maybe we should go away from the earth's surface, supposing that a monopole will approach the sun rather than the earth when it

enters the solar system. Or perhaps we should go to the centre of the earth. It is hard to believe that simple search experiments for monopoles will bear fruit. We really must think in depth about the vacuum and the structure of quarks and leptons first.

Search for the Substructure of Quarks and Leptons

M: Well, since quarks, as far as their interactions are concerned, come in three different kinds, three different colours as we say, and electrons come in two kinds, like electron and neutrino, quarks and leptons come in quintuplets, five particles which can be grouped together, and this may be a clue to a more fundamental theory of their structure and interactions.

R: What you are driving at here is the existence of another hidden and perhaps profound relationship between quarks and leptons, which we know very little about at present.

M: Yes. There are very surprising and little understood symmetries that connect quarks and leptons. What we have to do is to formulate a fundamental theory which explains these relationships, and then try to see what new phenomena this theory predicts, and then do experiments to test it.

R: Yes. I am thinking of such experiments. Very soon there will be an organized search for new interactions.

I am thinking in particular of the new German accelerator, the HERA project. One goal there is to scatter electrons from quarks by the end of this decade.

M: At much higher energies than can be done today.

R: Yes, at very much higher energies. What one intends to do is to collide moving protons and electrons on each other. Each will be moving against the other in its own accelerator, and they will be brought into collision with each other at a certain crossing point. Protons are carriers of quarks, and when electrons will collide with those at very high energy, and we will perhaps learn about possible new structures.

M: Yes, it is very possible that in these experiments we will learn more about the interactions that really produce quarks and leptons in the first place, and which also are responsible for the ratios of their masses. In a theory one can perhaps predict these mass ratios, as they may be a property of the vacuum. We hope that these experiments will tell us something about the quark-lepton vacuum.

Fig. 6.7: Aerial view of the DESY-accelerator complex in Hamburg where as of 1990 electrons and protons will be made to collide with ultrahigh energy in the accelerator facility HERA presently under construction.

(Luftamt Hamburg, Nr. 262/81)

R: That, indeed, would be a great achievement. What we are looking for is the discovery of a third type of fundamental vacuum. We have had the vacuum of quantum electrodynamics; we have had the vacuum of the strong interaction; and now we are talking about the vacuum of the substrong interactions. While the supercritical fields in quantum electrodynamics were created in nonrelativistic collisions, in which we brought nuclei together very slowly, we are planning in the immediate future to study the vacuum of the strong interactions by colliding very heavy nuclei on each other with relativistic energies. We find that a third stage of the discovery of the vacuum will perhaps come when we collide quarks and leptons at ultrahigh energies.

M: Yes, but we don't know today how high the energies have to be in order to find this third type of vacuum. The energies that will be available a few years from now are in the range of one hundred times the proton mass in the collisions of quarks and leptons. And so what one will probe is the region of distances of the size of one hundreth or one thousandth of the size of the proton. There may perhaps be visible structure there, but maybe this energy is still insuffient.

R: Then this great discovery will occur at CERN, where it will be possible to scatter leptons on leptons and later perhaps also on quarks at still higher energies. We hope today that when leptons and quarks meet each other at these very high energies, we will learn that a new vacuum of a characteristic dimension of one thousandth of a Fermi exists, and maybe we will learn from these experiments how to convert matter into radiation.

Structures in our World

M: But it is always very difficult to predict precisely at what scale such a new physical structure will appear. Consider, for example, an atom. The ratio of the size of the nucleus of an atom to the size of the atom is of the order of one to a hundred thousand.

R: Yes, it would be very disappointing if this scale factor reappears, because we would still not come to grips with the resolution of the vacuum riddle in the experiments during the next decade.

M: Considering that the progress of experimental physics has been such that one has gained about one order of magnitude in the resolution of structures per decade, it may not be too far away from us after all.

R: I would very much hope that we will both see this new structure discovered. But I, of course, wouldn't like just to live with the hope, and I am wondering if we do not have an idea about how to build a theory which would give us clue to these questions.

M: If we do not aim so high as to have a unified theory of quarks and leptons, but only consider a theory for a model that unifies the leptons to some extent, then there is such a model presently existing, namely the model which describes the unification of the electromagnetic and weak interactions.

Chapter 7

The Higgs Vacuum

The Carriers of the Weak Interaction

R. Berndt, I would like to discuss now how we can obtain a 'toy model' of vacuum structure which would permit us a very quantitative study of the various phenomena we have described in the previous sections.

M: The weak and the electromagnetic interactions form an ideal playground to build a practical toy model of the vacuum structure, and to learn in a simple way how to express the possibility that different properties of physical laws can arise in different physical vacua. Let me recall a few facts about the weak interactions: We discussed already the vacuum states connected with the electromagnetic interactions and the strong interactions. There is a third interaction in nature which has a very similar structure. That is the weak interaction, which is also carried by particles similar to photons or gluons, which we call the intermediate bosons. These particles have been recently discovered at the antiproton collider at CERN. But they differ from both photons and gluons in that they are very, very heavy. Now, it is not so easy to understand why they are heavy, because the theory which describes these weak interactions is almost identical in structure to the theory that describes the interactions transmitted by photons and gluons. So theoreticians came to think that maybe the mass of the intermediate bosons is a property of the vacuum.

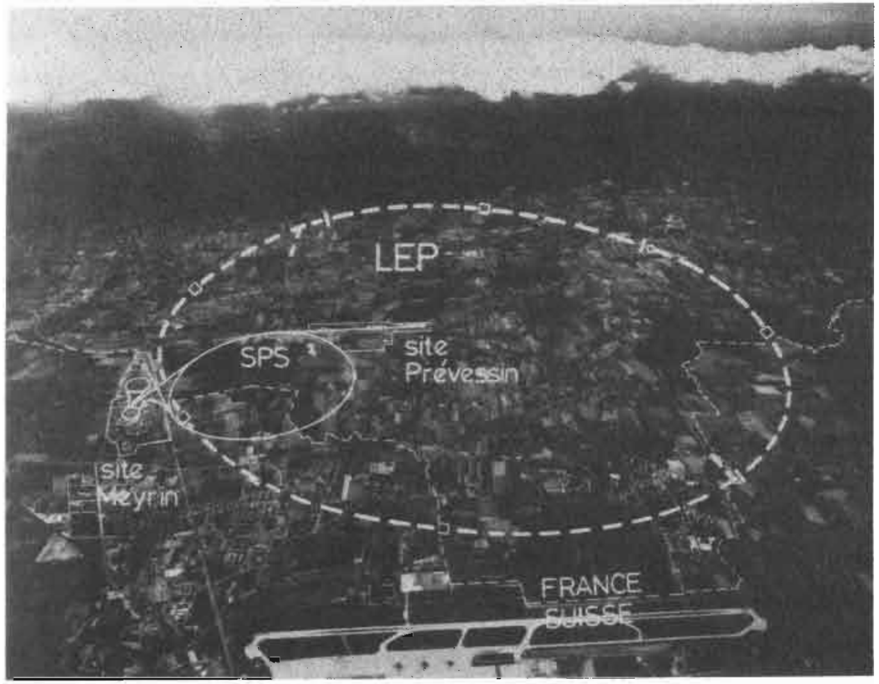


Photo CERN

7.1: Aerial view of the CERN complex in Switzerland. In the SPS ring the W and Z particles are being formed and experiments are also being planned to discover the quark-gluon plasma. The LEP tunnel is presently under construction.

R: That is a very ingenious idea. Does one really want to have particles which have different mass in different vacua?

M: Yes, why not?

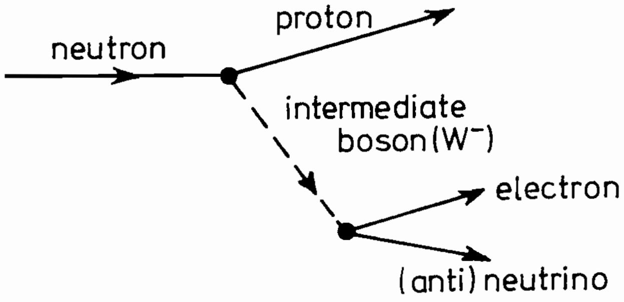


Fig. 7.2: The intermediate bosons W^+, W^- and Z^0 mediate the so called weak interaction. It is, amongst other things, responsible for the decay of the neutron and muon.

Particle Masses and Range of the Interactions

R: Well, previously we have seen that we could have quarks in the one vacuum and no quarks in the other vacuum. Of course, the bound state of quarks which we called a proton would then have a different mass in a different vacuum. But now you say that we should consider a still more complex structure. We want a particle to have heavy mass in one vacuum and to be perhaps even massless in another.

M: Yes. This is not as surprising as it may seem at first sight. For example, we know that in materials photons can be massive. This comes from the fact that photons polarize the material, and if we have some solid material having special properties, the polarization charge which will be carried along by the photon as it propagates through the medium actually can operate in such a way that the photon will acquire an effective mass. One sees this by the fact that the range of the electromagnetic interaction in such material is finite. It is screened by the charges which reside in the solid material.

R: Yes. I gather that what you want to imply is that it is the interaction of a particle, of a massless particle, with the structure of a vacuum that makes it massive.

M: Now let me also explain what the mass of the particle that mediates an interaction has to do with its range. This is again connected with the uncertainty relation of quantum mechanics. When a charged particle emits a photon, this is then absorbed by another particle, and in that way the electromagnetic interaction between the two particles is effected. The emission of the photon takes some energy, and therefore the photon can only exist for a short time, since the uncertainty relation allows the energy conservation to be violated only for a short time. Now, if the particle that is emitted is very massive, this means that it can only exist for a much shorter time than a photon, and therefore it can travel only a very small distance, and this limits the range of the interaction. So the range of an interaction is inversely proportional to the mass of the particle which transmits the interaction.

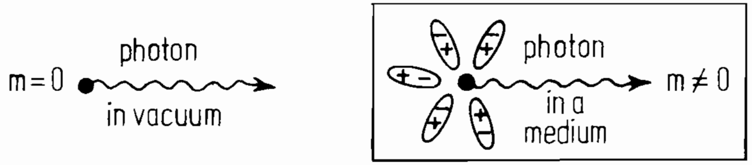


Fig. 7.3: By means of the polarization cloud (Debye cloud) which it carries around with it, the photon can acquire a nonvanishing mass in a solid.

R: So you would say that a massless particle generates an interaction which is infinite in its range.

M: Precisely. Now, the fact that the mass is connected with the range can also be taken as a clue that the mass may be connected to the structure of the vacuum, because this will also be characterized by a certain length scale, which in turn may be related to the mass of the particle.

R. It seems to me that what we are dealing with is a kind of screening, due to the large intermediate boson mass, of the weak interactions. We wish the vacuum to generate the mass, and one way to conceive of this is to think of an analogy to ferromagnetism. In principle, there is no reason for a ferromagnet to have a large magnetic field. It can contain domains in which the magnetic field points in different directions, and then a large piece of ferromagnet doesn't have a large magnetic field. However, one can in fact orient all the domains in the same direction, and then there is quite a strong magnetic field. Now that is exactly what I want to do in analogy, though not in detail, in order to create the mass which screens the weak interaction.

M We know that although in a ferromagnet the magnetic field has a specific direction, all the physical quantities like the energy contained in the field depend only on the absolute magnitude of the field , not on the direction. But tell me, Jan, what does this consideration have to do with the mass of the intermediate bosons?

Higgs Field

R: As I said, I am only seeking an analogy. The point is that we can generate a macroscopic value of some field, and that the vacuum can be characterized by this value of the field. We usually call such a field a Higgs field. Now in a specific toy model, what we do is to actually express the mass as being equal to the value of this collective field, the Higgs field.

Fig. 7.4: The Higgs field gives the intermediate boson a mass.

M: Very nice. This certainly would work. Now tell me, there are so many particles in nature which all have different masses, do we need a specific field for each particle?

R: No, one could in principle conceive of a quite complex field with many different masses arising from it, just as there are possibly many different fields of magnets. What we believe today is that there is one fundamental mass in a theory, and that other masses derive from it in some way via constants which are dimensionless. In particular, if this original, fundamental mass is provided by the value of the Higgs field, then the masses of the particles in the theory are generated by a very ingenious series of couplings between the Higgs field and these particles. And I should say that, of course, this sounds very ad hoc at first sight. But there are experimental predictions of such a scheme which can be very specific and some predictions have been extremely successful.

M: Can you give an example of such a prediction?

R: Take, for example, the scaling of the coupling of the Higgs particle to the other particles. Since we must generate all the different masses from the same scale, then all these couplings must grow in strength with the Higgs mass. So if the (Higgs) field which is responsible for the screening of the weak interactions were ever to be discovered as an independent particle, we could immediately predict what the strength of its interaction with the other known fields would be. There is just one unknown parameter, the Higgs mass; the remaining parameters are already given by the theory.

M: And this would, of course, be a dream of theoretical physics come true. But couldn't these so nicely modeled properties of the structured vacuum also be responsible for the breaking of symmetries in the interactions between particles?

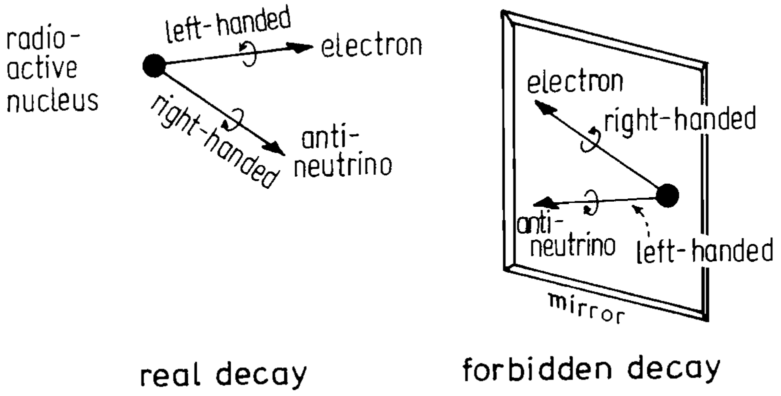
Vacuum and Symmetry

R: Let me first say a few words about symmetries in physics. We all know that it shouldn't matter if we describe the laws of physics in a coordinate system which has, as we call it, right-handed coordinates. To construct such a system, take your right hand so that your three main fingers point in three directions and call them X, Y and Z. That is how you define the coordinates of any event in this world. Now take your left hand and call the same fingers X, Y and Z. You will notice that the values of these coordinates for the same point in space change sign and that you cannot rotate your fingers such as to overlay all coordinates.

M: Now, we know that the macroscopic world is not symmetric under exchange of right handed and left handed coordinates.

R: We shouldn't expect it to be, indeed.

M: Well, we know that sugar usually comes as a molecule only in one spiral orientation, and we also know that the molecules that carry the genetic information in our cells also only come in one orientation.



real decay

forbidden decay

Fig. 7.5: The weak interaction violates the symmetry of reflexion: the reflected image turns the relationship between the direction of motion (arrow) and spin (ring) of the particles around.

R: Yes, I know that very well. But I think that this kind of symmetry breaking has a different origin. If one form of life dominates, it eats up other forms of life, and what you should really suppose is that for some time in the beginning there was both right-handed and left-handed genetic material. But then by some fluctuation the right-handed became more abundant, and the left-handed lost out to it; it was virtually eaten up and destroyed. As they were fewer, they couldn't survive. It had slightly different qualities, and since the world was more suited perhaps only by accident for one particular parity, as we say, the other one was displaced.

M: So it was perhaps some kind of accidental symmetry breaking?

R: Yes, I think that one should call it spontaneous symmetry breaking.

Violation of the Reflexion Symmetry

M: Now we know that the interactions, especially the weak interactions, are not symmetric against the exchange of left- and right-handed coordinate systems, and that radioactive decay of nuclei does not look the same if we look at it in a mirror. If we postulate that this is a result of a breaking of the symmetry by the vacuum, then couldn't we say in a similar way that in the beginning there was left and right symmetry in the microscopic world, and in some way the left-handed vacuum has gained the upper hand over the right-handed vacuum.

R: Of course, that is quite an interesting possibility. We must realize here that left and right-handed are really just names of things, and an arbitrary choice to some extent, because who knows what is the actual left and right hand. The right hand has a thumb on the left, and the left has the thumb on the right. So in the beginning there were two degenerate vacua, the one which was left-handed, and the other which was right-handed. However, we know that if there are two things which have the same values, they often repel each other. They don't like to remain the same. And so one of them became less likely than the other by a spontaneous type of event we have discussed for the right and left-handed genetic formation.

M: That brings me back to your example with the ferromagnet. The orientation of the magnet also depended in some accidental way on the history of the ferromagnet. But as we know if we look at it microscopically, in every ferromagnet there are various regions with different orientations of the magnetic field. So could it be that the vacuum prefers left and right-handed interactions in different parts of the universe.

R: I cannot exclude this possibility. However, I would be tempted to say no in view of the great uniformity of the visible universe which suggests a particular scheme of evolution in which also parity is uniformly and universally maintained. I would be tempted to believe that what is happening is that there is a Higgs field which gives different masses to the right and left-handed particles (see Fig. 7.4), for some particles at least. What I am referring to is helicity, i.e., if I look at a particular elementary particle such as an electron, I can say that it is moving in the direction of its spin or against it. I can correlate two things together, its momentum and its spin. Now for the neutrino there is an interesting possibility. Maybe the fact that we only find left-handed neutrinos and right-handed antineutrinos is a consequence of the fact that the opposite kinds of neutrinos are very heavy in our vacuum.

Restoration of the Symmetry

M: Well, that could be the case, and maybe future experiments will actually discover right-handed neutrinos. But let me come back to the ferromagnet once more. As we know, if we heat up a ferromagnet, it happens that at some temperature the orientation of the magnetic field will be destroyed, and we will restore the accidental breaking of the symmetry. I think the same thing could happen to the vacuum of the weak interactions.

R: Of course, we melted the vacuum of strong interactions, and so we will as well be able to melt the vacuum of weak interactions. However, the scale for melting the vacuum in strong interactions is one GeV, one proton mass as we have discussed. In weak interactions our scale will be generated by the characteristic mass associated with the weak interaction.

M: Which is about one hundred times the proton mass.

R: That is the difficulty. So even before we start thinking about this problem, we should anticipate that for the weak vacuum the change of its properties will be a hundred times more difficult to achieve than for the strong.

M: So our ideas will have to await experiments far in the future. But what would happen if we could actually perform such an experiment and restore the symmetry which is spontaneously broken by the weak interactions? Would it be possible in that way to convert left-handed neutrinos to right-handed neutrinos?

R: Well, maybe we wouldn't convert them. But what would happen, perhaps, is that we would find a neutrino which is neither right nor left-handed, and which is very likely quite a massive particle. And when the vacuum cools down again, the two different neutrinos would freeze out, and one would be very heavy and the other would be very light. Now this is an extremely wild speculation. We know nothing about this question today. We actually know only one kind of a neutrino, the left-handed neutrino. So my feeling about this is that we must face that we know so little here, and we shouldn't try to expand yet the standard of weak and electromagnetic vacuum. We must wait for a certain amount of guidance through experiment. We could, of course, take some guidance from principles of theoretical physics and from logical principles as well. But these, of course, do not tell us how things actually work nor how to recognize their elementary form.

Chapter 8

The Heavy Vacuum

M: As we discussed, one of the aims of our study of the vacuum is to relate dimensional constants like masses of particles to structures of the vacuum, and then to reduce the theory to contain only dimensionless constants, which can, in principle, be calculated from mathematical equations. This may work very easily with all the interactions we have discussed up to now, the strong interactions, electromagnetic interactions, and weak interactions. But there seems to be a problem with the gravitational interaction because it is long range, so it does not have a mass scale in the range of its interaction, but at the same time we know that the gravitational constant has a characteristic dimension, in contrast to the electrical coupling constant.

The Coupling Constant of the Interactions

R: What you really want to say is that the electrical coupling constant has a dimension of action which we can take out because we know its size already from other measurements. So we can construct for the electrical coupling constant a dimensionless ratio which we call the fine structure constant. But for gravitation I concur with you that we do not have a reference point. There remains an unknown fundamental unit of length. Of course, it could be the radius of the universe, but then the coupling of gravitation to matter should change with time.

M: But as we know, the typical length scale that is connected to the coupling constant of the gravitational interaction is not very large, but actually it is very, very small. It is many , many orders of magnitude smaller than the proton radius. The only thing that I can think of is that if such a small structure is found, we might be able to understand the gravitational coupling constant as the result of vacuum structure. But it must be a strange new kind of vacuum structure, because we would need a very microscopic vacuum structure normally associated with very high energies in order to explain a tiny coupling constant relevant to the low energy world.

R: I think this is the reason why this problem hasn't been solved yet. A solution will doubtlessly result in the understanding of extremely interesting phenomena. If we can understand the coupling of gravitation to matter, we could possibly be able to turn it on and off.

Gravitational and Inertial Mass

M: Now that is certainly a fascinating thought. Imagine if we could make ourselves weightless.

R: We can, as you know very well. Archimedes told us how to do it. We can, for example, float in water.

M: That is true. But it only gets rid of our weight, not of our mass.

R: That is precisely the point. Now we would like to dissociate these two factors forever. There is an inertial mass and there is a gravitating mass, and Einstein's principle of equivalence tells us that the mass which actually appears in the inertia of our body is the same as the mass which appears when we are attracted and gravitated to the surface of the earth.

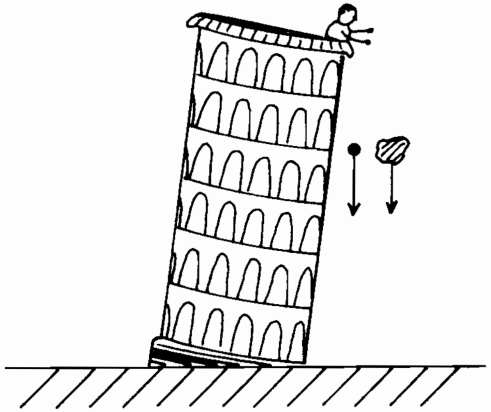


Fig. 8.1: With his famous free-fall experiments in Pisa Galileo Galilei demonstrated that large and small masses fall to earth at the same speed. From this finding Einstein developed the principle of the equivalence of gravitational and inertial masses.

M: That is not exactly correct, Jan. Einstein's equivalence principle tells us only that the inertial mass and the mass which gravitates are strictly proportional, and all you would like to do, as I understand you, is to change the constant of proportionality, not to change the fact that they are proportional.

R: Yes, indeed I wouldn't like to change the principle that Einstein has established, as it has proven itself so fruitful, but clearly if I had the possibility, by changing the structure of the vacuum, to change the constant that relates the gravitating to the inertial mass, it would be of great benefit. For example, I could make myself of much less effective weight, or perhaps better said, much less attracted by the gravitating body of the earth. I could then lift myself off the earth at a very slow speed. All I need to do then is to throw away small amounts of matter, and the principle of action equal to reaction would give me a certain directed momentum. And then I could just watch how I move away from the surface of the earth. However, as I don't have to overcome much force of attraction, I will move very slowly indeed because I still have a lot of inertial mass, and when I throw only a bit of this mass away, I don't acquire much of a velocity with respect to the earth. That way I could travel through space very easily.

M: Yes, that is correct.Now unfortunately we know today that this will certainly not be easy because the gravitational constant has been measured to be independent of time to a very high degree of accuracy and even remains uninfluenced by the expansion of the universe. So we really are looking for a new way to influence the vacuum which determines the gravitational constant.

R: I didn't want to say that this property of our vacuum has anything to do with time, although this would be a good assumption, since the size of the universe changes with time. So one could imagine that gravitation and the properties of gravitating bodies actually change with time as well. But my particular point is that this constant which relates gravitating and inertial mass carries a dimension. It could well be that this constant has something to do with the structure of the vacuum. So if I change the structure, if I learnt to influence the vacuum, I could change locally and under controlled circumstances the force that attracts us to the surface of the earth.

What does the Vacuum weigh?

M: That reminds me of the cosmological constant which Einstein introduced into his equations of General Relativity, and later again discarded because it was experimentally determined to be nearly zero. Now this cosmological constant essentially measures the amount of gravitating energy contained in the vacuum. Since we discussed that there are many different types of vacua, all of which have a different structure, in many cases a complicated structure, it is hard to understand why the gravitational effect of the vacuum is obviously so small.

R: Indeed we lack this fundamental understanding. What really is happening is that all these structures of the vacuum should carry a mass, right?

M: An energy density, to be more precise. We suggested there is an inertial and gravitating mass. Now a vacuum doesn't have much of an inertia. But it should have a gravitating mass. For some reason there is no gravitation of a vacuum. As we just pointed out, and Einstein worried so much about, there is very little gravitation, if any, from a vacuum.

R: The common way of hand-waving this problem away is to say that we renormalize the vacuum not to gravitate. But that's not true. We cannot do this because the universe develops with time. When we renormalize this constant away in the very early universe, we probably would have to struggle in order to have this constant still zero today, since the early universe was probably a melted vacuum. When the change to the frozen vacuum of today occurred, then this constant would acquire a nonvanishing value. So there is an intrinsic difficulty. My feeling is that the same mechanism which will allow us to control the connection between gravitational and inertial mass also will explain the present small value of the cosmological constant.

The Evolution of the Universe

M: Now, as you said, differences, energy differences, cannot be renormalized away. So if today the vacuum has almost no gravitational effect, then if at some time earlier in the universe the vacuum had a different structure, then certainly this vacuum must have had a strong gravitating influence. Without doubt it would have strongly influenced the expansion of the universe.

R: If one wants to compute the time sequence of the universe, one, of course, usually proceeds backwards. One starts from what one sees today and takes the established laws which govern the evolution of gravitating bodies - the universe is such a body in principle - and computes backwards in time.

M: Now as we well know, the universe is expanding and has been expanding for a long time. So in the past the universe was smaller and its energy density was higher than today. At some point in the past we arrive at an energy density in the universe that would have been sufficiently high to permit us to imagine that the vacuum of the universe had melted. This would happen, as we just discussed, at about one GeV per cubic Fermi, where quarks and gluons become deconfined.

R: Of course, this is only one example. It certainly would have happened more than one time for the different vacua.

M: Yes, but I think it is best to consider the transition we now have discussed at length here. So let us look at this one GeV per Fermi cube transition. At that point, when we go backwards, we must assume that the unit of volume of the vacuum would suddenly gravitate with a mass which corresponds to one GeV.

R: That, of course, would make the expansion of the universe much more difficult, one would think.

M: No, it turns out to be precisely the opposite. The reason for this is a somewhat curious feature of Einstein's theory of gravitation. As we discussed, a vacuum not only can have a nonvanishing energy, but also a pressure. Now in the absence of a constraint, be it high density or temperature, the melted vacuum would go over into the frozen vacuum that has lower energy. The region of space filled by the melted vacuum thus tends to become smaller. In other words, the melted vacuum is associated with a negative pressure, if the pressure of the frozen vacuum is normalized to be zero. Now in Einstein's theory not only mass gravitates, but so does pressure. Under normal conditions the gravitating effect of a pressure is imperceptibly small, but the vacuum pressure is large, so large that it overwhelms the gravity of the mass contained in the vacuum. The net gravitating effect of the melted vacuum is repulsive.

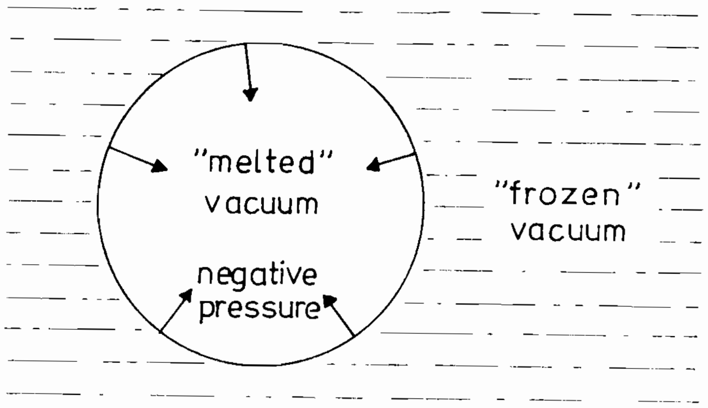


Fig. 8.2: The internal pressure of the melted vacuum is very negative, i.e. the vacuum would like to occupy a smaller space. The negative pressure results to a certain extent in an "antigravitational effect"

R: In a sense, one could speak of 'anti-gravity'. Normally the many particles contained in the hot, melted vacuum would more than balance the influence of the negative pressure of the vacuum itself. Just as the quarks moving in the melted vacuum contained in the inside of a nucleon balance the difference in pressure between the two vacuum states.

The superheated Vacuum in the Early Universe

M: Yes, but now we have to turn our movie of the evolution of the universe around and look at it running forward. So originally the universe must have been filled with the melted vacuum, with many particles contained in it which more than balanced the negative pressure of the melted vacuum. Now as the universe expanded and cooled down, at some point in time, the positive pressure of the particles was no longer large enough to balance that vacuum pressure. At that moment the transition to the frozen vacuum should have taken place, confining the quarks to the interior of microscopic regions of melted vacuum called nulceons and mesons. However, if the expansion proceeded sufficiently fast, then the transition to the frozen vacuum could not occur immediately but only sometime later, and the universe would spend some period of its evolution in the 'wrong' vacuum state, with its negative pressure no longer balanced by the particles contained in it.

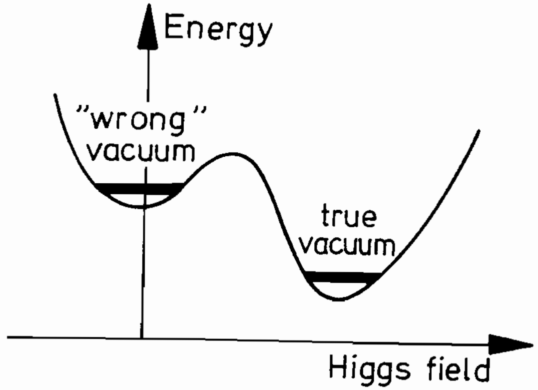


Fig. 8.3: When the universe cooled down, the Higgs field was possibly frozen in the "false" vacuum. Only after a longer period of undercooling did a sudden change into the energetically lower, "true" vacuum take place.

R: Now that reminds me of what happens when you refrigerate water quickly below the freezing point. It will not turn into ice immediately, and instead you can have supercooled water for a considerable amount of time. It has all the physical properties of water, only that it is in some kind of unstable state. When you shake a bottle with supercooled water, it will freeze to ice in an instant, bursting the bottle violently.

M: Yes, this is precisely what may have happened in the early universe. The supercooled, melted vacuum existed for a certain period of time, until at some moment it began to be converted into the frozen vacuum in a process very much like an explosion. The frozen vacuum started in small bubbles which grew at the speed of light. In the conversion process, the latent heat of the meltec vacuum was transformed into real thermal energy, and the universe was heated up again.

Explosive Development of the Early Universe

R: But the really important period was, of course, the one in which the universe contained the supercooled melted vacuum. The gravitational action of its negative pressure actually pressed the universe apart. As we said, it works as a kind of antigravity.

M: Right, Jan. In fact, the expansion during that phase can be calculated to be exponential; that is, the size of the universe would double in a fixed time, would double again in the same time and so on.

R: Such a process is called inflation...

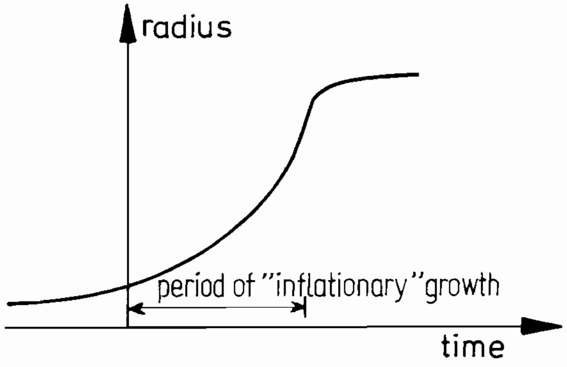


Fig. 8.4: During the period when the Higgs field was frozen in the "false" vacuum, the universe increased its size at an exponential rate ("inflationary growth").

M: You mean like inflation of money?

R: Yes. This inflationary scenario is being thought of as an important aspect of understanding the structure of the universe today.

M: Now, the inflation of money has the effect that it equalizes the differences between rich and poor people because money becomes worthless after some time. So one could also imagine that a very rapid growth of the size of the universe could lead to a smoothing of the small inhomogenities in the distribution of matter in it.

R: Yes indeed, this appears to be a natural consequence when the universe grows very rapidly. It is also necessary, because although locally it is extremely inhomogeneous, globally the universe appears to be a very homogeneous physical system.

M: How do we know that?

R: We can for example measure the number of stars per unit of volume if we determine their distance from the surface of the earth. In that way some large void regions have been discovered recently. However, on a large scale one really can say that the universe is surprisingly homogeneous. For many years this remained an unsolved puzzle. Actually if you were to think of an explosion of any kind, Berndt, you would discover that it would most likely lead to an inhomogeneous distribution of fragments. It is hard to imagine an explosion where everything remains homogeneous. Thus there must be a special process like the inflationary expansion as just mentioned.

M: Further we know that the echo of this explosion of the universe, namely the background radiation, is extremely homogeneous, so we really know that the expansion of the universe must have been homogeneous for a very long time.

Background Radiation: Modern Ether

R: Yes. Let me now change the subject somewhat: This echo of the birth of the universe is actually a very remarkable thing. You know, the vacuum is usually misunderstood and was misunderstood for many years. In order to have waves propagating through the vacuum people conceived of ether. But we do have an ether! This is the background radiation that you have just mentioned.

M: So you mean that Michelson's experiment was wrong after all?

R: Michelson set out to prove that the velocity of light is the same in all directions of space.

M: And independent of the motion of the observer.

R: Yes. Now, that does not prove or disprove the existence of an ether, as Einstein very clearly pointed out. Einstein was very careful to point out that the laws of physics, which are relativistically invariant, make observation of an ether impossible. However, what he didn't consider at that time was that even when the laws of physics are relativistically invariant, the state of the universe can depend on the initial condition, on how the universe started. And where it started. The frame of reference which is defined by the expansion of the universe is a preferred reference frame in many ways. That is precisely why the Michelson-Morley experiment can be explained, yet I can still talk of an observable ether, for the background radiation provides me with an absolute frame of reference in which the universe started. It does not, of course, provide a medium in which electromagnetic waves travel, but I can tell you in principle and also in practice what velocity the earth has with respect to this ether. And all our spaceships at any place in the universe can always tell at what velocity with respect to the ether, and therefore to the earth they are moving.

M: Of course, that is only true if the spaceship is far away from a major inhomogenity, such as a neutron star or black hole, which disturbs the ether of background radiation.

R: But that is a practical problem which doesn't concern us here. The crucial point is that we have an absolute frame of reference provided for us from the beginning of the universe by the frame in which the inflation of the vacuum occurred. And that, of course, makes the vacuum state much more interesting again.

M: Now this also would mean that the universe, the real universe, might actually be much, much larger than the part we see today, because the velocity of light is finite and therefore we cannot look infinitely far. By looking into the sky with a telescope, we can only see as far as light can have travelled since the beginning of the universe.

Our Universe: an Old "Accident"?

R: Yes indeed. Actually, it could be that the real universe is an extremely large domain, and that what we are seeing now is perhaps what has been started by some disastrous experiment performed some twenty billion years ago by a post-graduate student in order to test the structure of a vacuum of another universe. Then what happened was that the vacuum was suddenly changed, and the result is our universe. I don't want to go deeper into this very weird idea. And perhaps we should cut it out later from the text...

M: No!

How Many Dimensions does our World have?

R:...but what really matters is that our universe, the visible universe, can be (a) a small fraction of our entire universe and (b) that the entire universe can actually be embedded in part of a higher dimensional space. Basically you can think the same way of a sphere. You can live on the surface of the earth, but you can't live inside. Maybe that is the situation with the universe.

M: You mean, the possibility that there are more than four dimensions in the world, more than the three dimensions of space and the dimension of time, but that in some way we are frozen in our movement in the other dimensions, so we cannot really move at will in these dimensions.

R: I don't know enough to answer this question.

M: But do these considerations have any physical reality?

R: Yes, we may be moving in these dimensions without noticing it. We have been discussing the properties of, for example, mass. One can show that mass is effectively created if there is a constraint for motion of a body in three dimensions. As an example, take water flowing down a surface. If you constrain it by building a narrow gutter, then it will not be able to flow as quickly. By constraining the motion to a particular spatial structure, we simply introduce an additional inertia, a mass. So it could well be that the problem of explaining the masses of elementary particles is associated with the fact that we are thinking in the wrong dimension of space.

M: Actually, practical models for this can be built and used for experiments in solid state physics, where one can construct two-dimensional solids. One can then investigate the motion of electrons when they are constrained to move in only two dimensions. These materials exhibit some very surprising properties.

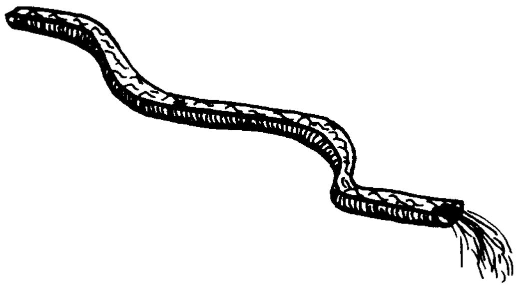


Fig. 8.5: Water flowing in a winding channel is delayed in its flow. One could say as well that its inertial mass has been effectively increased.

R: Yes, these models exist, and they cause me to have a very worrisome thought: maybe all our understanding is a misunderstanding. Maybe many of the properties of the particles which we have introduced and which we have just described could be reflections of the multidimensionality of space. So it could well be that our world is actually very highly dimensioned, and that we are compactified to its surface in the three dimensions.

M: Now that certainly would again be an evolutionary property of a vacuum, which would be responsible for the freezing of the other dimensions, and it is a fascinating thought that at some time we might be able

to melt this vacuum and obtain new dimensions to move freely in.

R: You realize, of course, that if that were true, we would still have a maximum velocity very nearly equal to the velocity of light. But we could get from one point to another much quicker. The point is that if you think of yourself as being confined to the surface of the earth, and somebody else can go freely through the centre of the earth, he will reach the other side faster. We would be travelling through hyperspace just like in the science fiction books.

M: Although all this sounds very much like a science fiction novel, these theories are seriously considered today. When I open a current research journal and look into the theoretical section, I find that there are many very serious papers dealing with these questions. Understanding the vacuum is radically changing our understanding of the universe.

Historical Outline: Vacuum

Development of the Descriptions of the Vacuum

ca. 500 B.C.	Parmenides (founder of the Eleatic School of philosophy) teaches that the "void" is unnecessary for a description of the world
ca. 450 B.C.	Empedocles describes experiments with the so called "klepshydra" which is used to demonstrate that nature does not allow the creation of a macroscopic vacuum ("horror vacui")
ca. 400 B.C.	peak of the atomic teachings under Democrit who stated that all material is built up out of indivisible atoms moving about in the micro-vacuum
ca. 350 B.C.	Aristotle supports the theory of "horror vacui". The entire space is filled with the four elements (fire, earth, water, air) and with 'ether'. The terms 'ether' and 'vacuum' can be largely viewed as synonymous
1643/44	Torricelli's barometer experiments

1650	Otto von Guericke invents the air pump and demonstrates the pressure difference between air and vacuum
1687	Newton describes the classical conception of absolute space in his main work "Principia Mathematica Philosophiae Naturalis"
ca. 1850	Robert Boyle shows that sound cannot diffuse in the vacuum whereas light can pass through unimpeded
1873	Maxwell develops the uniform theory of electromagnetism and predicts electromagnetic waves propagating in the ether
1887	The Michelson-Morley experiment shows that the vacuum is not filled with a material ether
1905	Einstein develops the special relativity theory on the basis of the unobservability of the ether. The equivalence of mass and energy arises as a consequence from Maxwell's theory of electromagnetism
1915	Einstein develops the theory of general relativity on the basis of the equivalence of inertial and heavy mass. Space (vacuum) is now considered as curved

1925 - 27	Development of quantum mechanics. Heisenberg formulates the uncertainty relation
1932	Anderson proves the existence of the positron in the cosmic high-altitude radiation
1930 -35	Heisenberg, Pauli, Dirac and others develop the quantum theory of the electromagnetic vacuum. Prediction of the vacuum polarization and the light-on-light scattering (Delbrück scattering)
1947	Lamb and Retherford discover experimentally the splitting of the states in the L-shell of the hydrogen atom and thus prove the existence of virtual particles in the vacuum
1946 -50	Feynman, Schwinger and Tomonaga develop quantum electrodynamics in its modern form and introduce the renormalization of the vacuum state
1949	H.C. Casimir shows that the zero point energy of the vacuum is variable and that this effect can be measured
1960 - 65	First assumptions that the vacuum state can have an inner structure (Higgs fields, Goldstone bosons)
1965 - 70	First practical application of vacuum structure models. Formulation of the unified theory of electromagnetic and weak interaction by Glashow, Weinberg and Salam. Prediction of the intermediate bosons W and Z
1974 to date	Attempts to construct a unified theory of all known interactions. The possible importance of the structure of the vacuum for understanding the nature of gravity and its role in the development of the universe is recognized
	Experiments are carried out to prove the formation of a charged vacuum in strong electrical fields
1983	Discovery of the bosons W and Z at CERN and proof that their masses were quite accurately predicted on the basis of the known vacuum structure of the weak interaction. Nobel Prize 1984 for the main scientists involved in the CERN experiments: C. Rubbia and S. Van der Meer