



UNIVERSITY OF CAPE TOWN

*Why and How in
Theoretical Physics*

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WHY AND HOW IN THEORETICAL PHYSICS

by

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Mr Deputy Vice-Chancellor, Mr Deputy Principal, Honoured Guests, Ladies and Gentlemen - Thank you for being here tonight. This is an opportunity when we can take a slightly broader view, so I would like to share with you, firstly my views on how theoretical physics fits into the general intellectual endeavour and secondly, what is of most interest to me. I will, of course, illustrate the different concepts with examples from my own scientific career and beg your pardon for these slightly more professional excursions into physics.

Certainly, the first thing to explain is: What is theoretical physics? Who needs it, and why?

Is it not sufficient just to perform skilled experiments?

To appreciate these questions, try to find, without further advice, the message I left yesterday somewhere within the metropolitan area of Cape Town. Clearly, you either stumble on it, or if you search carefully you will find this message - but, as you can imagine, only after a very long time if you are searching without guidance or any indication from somebody who perhaps has an educated feeling about where I might have left it - at home or maybe at work. But even if I left it somewhere on my way from home to work - you still will probably never find it. And if you do not even know what this message looks like, very probably you will not recognise it *if* you do find it. So there is the second part of my example - even if you find the message, you don't know how I have written it. Or on what type of paper. Or even what it looks like. So even if you stumble upon it, you might just ignore it. And so I think you are beginning to feel why I am standing here in front of you. *I am trying to help you find such messages!*

It is a historical fact that a very large number of accidental discoveries were made but not recognised as such, before a conceptual understanding guided the eye. If you don't have any kind of guidance, right or wrong, there is no reasonable chance for anybody to uncover the truth about nature.

You now know exactly which way I am taking you in this lecture, but let me point this out more directly. Physics is concerned with the understanding of the natural world around us but theoretical physics attempts to uncover the system in the madness called nature, without knowledge of guiding principles, but given certain challenging experimental observations or inconsistencies. The last point is a very important one - not everything that we do is consistent - not everything that we see or know is consistent - but sometimes it is difficult to recognise that there is an inconsistency. That there is a problem. The issue is to pose and see the right question.

It is now time to locate theoretical physics more precisely among the different sciences, since it is not only a popular belief that to the layman it is perhaps the most misunderstood scientific discipline.

Now before we localise theoretical physics, I have to first localise physics among the different sciences. Of course we have certain ideas of what science is - I will not dwell on this point. But physics is a much more specific statement, and I would like

to spend some time on it. To this end I will compare physics to two disciplines which are perhaps better established in your perception. I will proceed, as is done by physicists, by looking at an example. The example I have chosen is to look at the kind of questions one may pose. I am not a philosopher so I am not sure if am indeed asking the right question here, but if I were one, I would ask the question: Why is there a universe? Why is there life? But the basic things which I, as a physicist, am interested in, are much more down to earth. However, a physicist would *not* ask: How would I build a road or a train? It is known how to build these things! It is just a practical issue! Maybe not everyone can build them - but it is certainly not my subject as a physicist. What is my subject then? Well consider such questions as: How matter was created. How did life begin on earth? How or what is human intelligence? How or what is the vacuum?

I will dwell, in my lecture, on that last question. By this time you will recognise that physics questions are *different*. But is it really physics if you ask 'How did life begin on earth?'. *YES*, because all other sciences, such as chemistry and geology, which use physics are basically fields in applied physics. And those of you who are familiar with the answer to this question, appreciate that it is a very physical one! Exactly the same remarks apply to the subject of human intelligence. When I discuss the vacuum, you will see why there is a problem here.

It seems that there is a bit of both philosophy and engineering in my questions, but there is also a new dimension in them. Namely: I accept the way nature is and do not question its existence nor do I attempt to use well-established knowledge to construct the answers. My questions seem to be either trivial, and have a metaphysical answer only, or to be outside the set of possibly answerable ones.

I think the right way to proceed is simply to draw a horizontal line and to say: There are two types of questions - questions of type 'How' and questions of type 'Why' as shown in Figure 1.

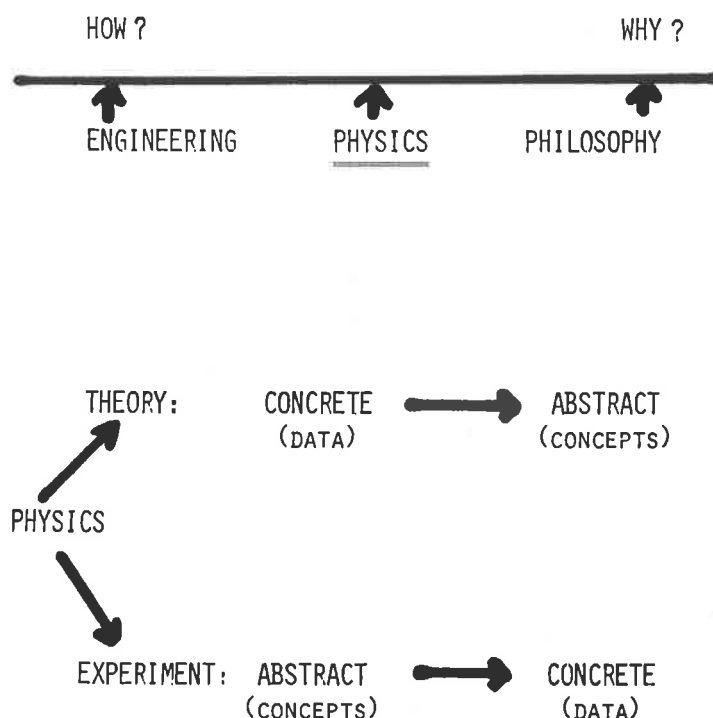


Figure 1 : Physics and Theoretical Physics in perspective

I don't want to put any kind of scale between these two points, because I don't think that one exists. The fact is that physics asks both questions and the type of questions we ask must contain both of these elements. So physics is situated somehow above engineering and philosophy and not in between in the sense that there is a distance. Physics combines both aspects and adds a new dimension to them!

From this attempt at localising physics, in terms of the 'How' of engineering and the 'Why' of philosophy, arose the title of my lecture - I felt compelled to add 'Theoretical', as all my examples will be drawn from my own work. Of course one can use this title in many other subjects, but in physics its meaning is quite a subtle as we have just seen.

I hope that I have argued convincingly that physics, as a discipline, is extending the knowledge of engineering and philosophy and that each physicist is eager to be an amateur engineer and philosopher and indeed, he should be in order to successfully uncover the secrets of nature!

We come now to the second problem which I have and that is, I would like you to understand what theoretical physics is.

Is there a separate and independent science called theoretical physics?

Consider again the second half of Figure 1. It tells you, that in my view, *theoretical* physics has, as a task, the organisation of data or, in general, any information into ideas and concepts describing how nature works. The opposite role, as I see it, is played by *experimental* physics. Existing ideas and concepts are converted into new data and an experimentalist is held in highest esteem when he succeeds in proving, by exception, an established concept or idea to be wrong. Remember here that it isn't his task to prove anything. It is one of those philosophical issues: We can never prove anything about nature! The only thing that one can show is that something thought about by some theoretical physicist, is wrong. Of course that is a very destructive attitude, but actually it is true that great discoveries were made by proving, experimentally, that something well-established or some belief, or some concept, was very wrong. I don't need to go into details of this because we have a good feeling that this is actually so. But you should remember the fact that experimental and theoretical physicists work in opposite directions. The methods and thinking we employ are against each other - orthogonal, as one says in physics and mathematics. And that is a very important thing, because actually the way one thinks is very important and it is very important *to be capable and to be allowed to think differently*.

One can even go to the extreme of asking: Is there not one man who can combine both these aspects in himself? Of course it is possible! It is a question of effectiveness. You can go back in history and look at Leonardo Da Vinci. He was, and I think everybody would agree, the last universal natural scientist. And now of course, you can ask: Who was the last universal physicist? Perhaps that is already beyond us or perhaps there will still come one last physicist - the last man who actually combines those two areas in himself. I can give you an answer about the past - Enrico Fermi was certainly the last physicist of whom I know. He has contributed, in an extremely distinguished fashion, to both experimental and theoretical physics. Enrico Fermi died in the 1950s but he made his contribution in the '20s, '30s, '40s and '50s. Now if I look at each individual important man of physics today, I find that he is either an experimentalist or a theorist - there is not a single one who combines both these aspects in himself. Thus, Enrico Fermi, until another man does it again, was the last physicist on Earth? And the first theoretical

physicist was Isaac Newton. He definitely was the first theoretical physicist. And he wasn't the last! He was followed by such names as Maxwell, Planck, Einstein and many others.

I hope to have convinced you, at least partially, if not fully, that there are really several fields of physics now: two, if not more. I have not discussed what is called applied physics. Neither have I discussed astrophysics, or astronomy - there are all those subjects which one can view as being separate sciences or being part of theoretical or experimental physics. I think that such a discussion would take us too far, given the time that we have, so I would rather talk about a few worthwhile examples from my own scientific life. Let us begin with the question concerning the vacuum: I initially raised four questions. I could, of course, talk about the first three as well, but I feel that since the vacuum is something not in question at all, I owe you some further explanations in order to illustrate why there is a problem at all. This example is so good since it also illustrates the issue that a theoretical physicist must always question the obvious. He should never question something which is very intricate - it must be so obvious that it seems not to be a question at all. It must not even seem to be within the set of answerable questions. It must be about something which is *obviously* not in question.

HOW OR WHAT IS A VACUUM?

In the Encyclopaedia Britannica we read:

'Vacuum is ... any region of space devoid of matter'

Hence, it seems that the subject is settled and not of interest - and that's it! This statement is not correct. Why is it not correct? Well, let us think about it. The statement in the Encyclopaedia Britannica assumes that classical mechanics controls the laws of physics. In classical mechanics everything is certain. Remove all matter from a certain region of space and what you are left with is actually what that statement says: A space devoid of matter! But we live in the era of *quantum mechanics*, and the concept of *certainity* is substituted by the concept of *probability*. Quantum mechanics is indeed nothing else but this one single statement. In other words, we cannot be *certain* anymore that we have a region of space empty and devoid of any matter. The uncertainty principle is a law which one uncovers, experimentally, but it was formulated as a concept by theoretical physicists, of course! The uncertainty principle implies that in a certain period of time, a certain amount of matter may be created, may appear, and subsequently disappear. This is a very quantitative statement and I illustrate the involved numbers in Figure 2. First we notice that 1 gram of matter will only appear for at most 10^{-48} seconds. Now that is an awfully short time, so we have to look at smaller amounts of matter to be created, in order to see where quantum mechanics begins to play its important role in our lives. Clearly, it will not be when we deal with amounts of matter which are of the order of a gram, i.e. something which I can take into my fingers and feel. I can ask: What if I consider the smallest unit of matter I can imagine, something like one atomic unit which is one hydrogen atom? Now for how long can a hydrogen atom appear? The answer to this is also shown in Figure 2. It is 10^{-24} seconds. That is actually still a very short time, though it begins to approach the orders of magnitude we deal with today. From one atom we now go to look at what happens if I want to create a virtual - virtual is the language one uses here - lightest massive particle we know of, which is the electron. An electron, it turns out, is so light that we can have it for 10^{-21} seconds in a domain of space devoid of matter. Now that is actually quite a sensible time, as it turns out. It is very near to what one can

UNCERTAINTY RELATION

$$\Delta M \Delta t = 10^{-48} \text{ g sec}$$

FLUCTUATING VACUUM

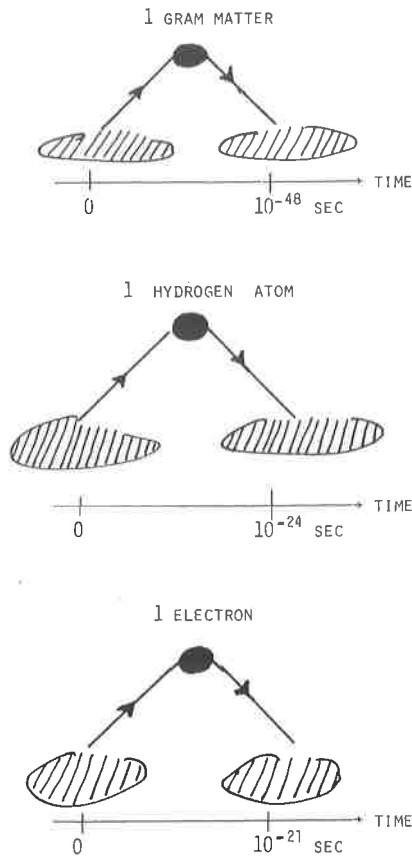


Figure 2 : Uncertainty Relation and Fluctuating Vacuum

measure. In other words, in vacuum, I will have a good chance of seeing a virtual electron if I do a measurement within 10^{-21} seconds. That is exactly the issue of quantum mechanics: We lost the certainty of having an empty space. But that of course is a very wonderful thing and the subject begins to be an interesting one scientifically.

But, taking this argument further, we can argue that there is no reason for the vacuum to be a simple object. It should actually acquire a structure. The mere fact that we can have one virtual electron of course invites the question: Why not three? Or maybe two here and five there! Or 21 in the moon and seven in this room. How do we know where to stop? We must come to the conclusion that the vacuum can be a highly structured object. And hence, it certainly is an object subject to physical investigation. The moment we believe in quantum mechanics and QM is experimentally well verified, we are obliged to believe that the vacuum is structured. But a structured vacuum would normally be multivalued, that is, 'nothing' comes in many different ways! Depending on circumstances, how the vacuum arose and what constraints were exercised, quite different situations can be reached. We know the laws of physics in sufficient detail for these vacua to be determined and their presence identified experimentally.

Of course I must regress at this point, since all I have said about the vacuum hinges so much on quantum mechanics. Here is a question a theoretical physicist should ask:

'Why is there quantum mechanics? Or maybe: Is it there at all?'

Normally, we would not be inclined to pose this question except if we had reason to mistrust our basic understanding of nature! Of course somebody can always say: I don't believe in quantum mechanics! Many physicists in the 1930s simply said so! You see this problem with the fluctuating vacuum and so on - there are other such problems. Now you really begin to question the basics! One actually can reject quantum mechanics *per se*! Einstein belonged to the class of people who refused to trust quantum mechanics. Many others believed that it was just an invention to guide us on how to compute things - and actually this is how it is *de facto* nowadays - we do not try to understand it in terms of its classical limit, but simply use it. QM is as well established by experimental data as anything in our knowledge about nature. But we can of course, and indeed we are obliged to, ask the question:

'What is it that makes quantum mechanics necessary?'

I think it is one of the most important questions and it is certainly within our knowledge to pose it. It is one of the important issues that some theoretical physicists are questioning now and there are actually conferences on the subject - not for philosophers - but for physicists!

Quantum mechanics is certainly a field of study - and a very important one - but nonetheless I have no reason not to believe that the vacuum has a structure. If vacuum has a structure, there is a second very important conceptual step which one can make right away: If it has a structure, the vacuum is not one thing. I can have many vacua. There is no reason to believe that the vacuum is unique, in other words, the world can be full of different vacua. '*Nothing*' comes in different shades. That is very exciting because if you have vacua in different shades, how do you know that while it now comes in grey, that it will not appear in a different shade tomorrow? So there can be changes - transitions between the different vacua. That, of course, is a very worrisome thought. There are serious investigations questioning. Are we in the right vacuum now? This is a very important question. If we do an experiment will it not induce a change, a transition from one vacuum to another. That would be a catastrophe, since we would not be here anymore! We are part of a vacuum in which we live. And if there were these changes, then we could not exist anymore. Now fortunately, let me ascertain very quickly and give you an answer, it has been estimated that no experimental machine or accelerator that will be able to be built until about the year 2000 will cause us trouble. You see we know what can be built up until then in good approximation. We can extrapolate our technological means for about 20 years. In that time we will not reach what has not been reached by nature itself: in particular, there is a lot of radiation which impinges on the earth from the sky. So from the known kinds of cosmic radiation, we can deduce that if we were in the wrong vacuum and if one experiment were to change the vacuum, this should have already happened sometime in our past due to cosmic radiation. Thus we are in the right vacuum! At least one which is stable to present experiments. But it may be unstable under other circumstances! But soon, i.e. next century, we will be able to build up experiments which will probe beyond the limits that nature has itself explored. Doubtlessly, a very challenging, if not frightening, thought!

My own work on the vacuum began in Frankfurt when I was a young student in 1970. I was very lucky at that time to have met *Walter Greiner*, who is the Professor of Theoretical Physics in Frankfurt. He was my mentor and teacher for many years. And he interested me in these issues by saying that he was also ignorant of these things and that we both had to learn what the vacuum is. He made a wise choice, not only to have the right student, but also to have the right problem.

Walter Greiner is a man able to recognise that something which is not a problem actually is one. And the vacuum has become a very important subject in physics subsequently - but you must know that this interest dates back to the early 1970s. We studied the vacuum structure arising from properties of electrically charged particles and determined the conditions under which transitions between different vacua were expected.

As we have just decided that the transition of the one vacuum to the other can occur, we have to first create *local* circumstances for such a transition. Secondly, we must be able to observe such an event. Now, as it happens, when we think of a vacuum decay for charged particles (I assume here that everybody knows what electrical charge is), we recognise that to observe such a decay, we must observe emission of charged particles: the appearance in such experiments of the lightest charged particles, electrons or their anti-matter companions the positrons, are likely to be the observable effect. So we must look for positrons. But there will be plenty of positrons anyway, since positrons are copiously created in many ways in today's experiments. So one has to design special experiments in order to see what one wants to see - it is not enough to have the right idea. One has to invent a way of seeing it. This is also very important in theoretical physics - not only must you ask the right question (of course you must be able to get the right answer) - it's also important to be able to make a proposal concerning how somebody can verify that these concepts and ideas are false! I said false, since you can never prove something to be true. All I can claim is: if this doesn't work, then I am sure that I am wrong - that is all I can say. And all we ever find is just a nice and simple way of understanding the observed phenomena. So, by assumption: Truth is beautiful!

Let us return to the study of the vacuum and the experiment about it: I assume that we all know conductors and insulators. Further, we know that a vacuum is normally a perfect insulator! There will be no sparks moving across the vacuum, nothing which will carry charge. The point I want to make is that this is not true anymore in quantum mechanics - even if you prepare empty space, it is not really empty as we have seen. When we apply a strong electric field to it, the vacuum will spark. Virtual matter is always there and all you need to do when you apply the strong electric field to the vacuum is to create the conditions to materialise what is already there. Of course you will now wonder why, if one looks around, one doesn't see positrons everywhere. The point is that one has to have a very strong electric field - and it turns out that the only way to create sufficiently strong electric fields in the laboratory right now is by bringing two heavy nuclei together. As you know, atoms consist of electron clouds and on the inside there are very small objects - atomic nuclei full of electric charge, surrounded by strong electric fields. When you bring two such nuclei together, then their electric fields are combined. Therefore, it would be even better if I could have brought more than two nuclei together, except of course, this idea is impossible to realise - I could not coincide more than two nuclei in time and space!

Now let me show you how one deals, in practice, with the positron production. This is a little bit more complex and you may skip these five minutes for which I beg your pardon. In Figure 3 I will show vertically, the insulator gap of the vacuum. It takes the energy of the two electron masses to create real matter - an electron-positron pair. Now normally, as we have just discussed, it is very difficult to bridge this gap. But consider a strong electric field characterised by a localised electric charge. Then I can consider electrons which are bound in this field as functions of the charge depicted horizontally in Figure 3. I can, particularly, look at the energy that these electrons have - these are the lines in the gap. Now, normally we know

that if you look at a hydrogen atom, there is only a very small binding effect - very, very small compared to the masses of the particles. But if I made the electric charge so big that it corresponds to the charge of two uranium nuclei, then it turns out that these electrons are bound by twice the rest mass. Actually, a little bit more for the case of interest to us.

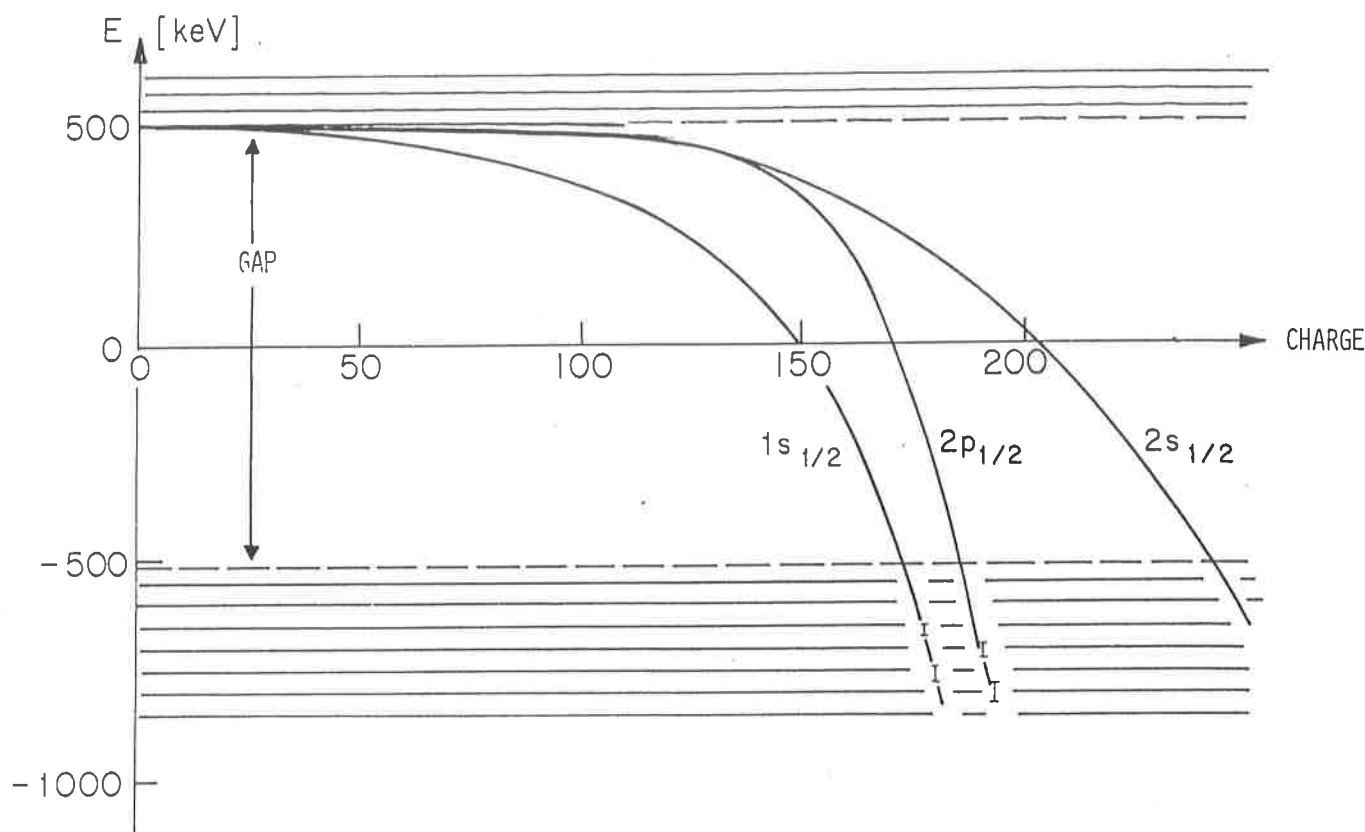


Figure 3 : Bridging the gap between the particle and antiparticle states

Then a connection is established between the one and the other band and the vacuum will now support the carriers of charge. A positron is emitted, signalling that a transition to a charged vacuum has occurred. The normal vacuum is neutral and the new one charged. Now that process is very exciting because one can show, by its observation in an experiment, that vacuum has a structure and is able to make a transition before your eyes. Fortunately, only a small region of space, where the electric field is the strongest, undergoes this change. All this is very simple conceptually, but difficult to accept - and many of my friends question if we really have understood this process. They claim that something very complex must happen - vacuum must remain stable. It must not be able to make a local transition, no matter what you do to it. So they searched for and proposed (as we did as well) anything imaginable that would prevent this vacuum decay from occurring. This search went on for several years and it turned out that nothing could be proposed that would agree with our present experimental observations and at the same time would quantitatively change the behaviour of the vacuum. Nothing consistent has been found in ten years - this is the particular test which, as mentioned, should be applied to any new concept. You verify the new concept against all the other experiments you can imagine. If you do not find any possible consistent modification which would prevent the vacuum decay, then you should assume that this is the truth, and then go to an experimental physicist, a friend, and say: If you bring two uranium nuclei together and you don't observe the positron, then I am in

trouble. But if you observe it, then it is OK and it is consistent with my new theory.

That is what happened and the chase for positrons in uranium-uranium collisions began in 1976. Of course that was a long chase. Because, as I pointed out to you, positrons are easily produced in other reactions. So a new idea really had to come before one was able to untangle the data. And that idea really is very simple! It's not only nice that positrons tell us about the vacuum decay. They are also witnesses for a very short moment of the nuclear collision. Maybe nuclei stick together creating a very complex large nuclear system - a super-heavy nucleus? Well, once that was recognised, there was only a short step to take in order to devise the right experiment. Let me just briefly show you in Figure 4, what an experimental result looks like if you do it the right way. If you measure the number of positrons as functions of energy, you notice on top of a smooth background distribution that there is suddenly an emerging peak. This structure clearly doesn't belong there. One further considers a control measurement in such different circumstances that this structure is expected to disappear. And it does! So there is something happening - there is a signal of vacuum decay.

But you still cannot simply say this is the effect we have been looking for. You have a signal but what is the chance that this signal comes from an effect which has no connection with the vacuum decay. There are so many things that can happen. You must actually go and do experiments in order to exclude all the complex processes you have thought of. What is helpful is that the other phenomena will reoccur in different circumstances. So now the experimental consistency of the assumption that the observed peak is actually a vacuum decay is carried through. You cannot simply say: I have discovered it. Again a very narrow cooperation between theory and experiment is needed. The new concept is followed by an experiment and then the experiment is followed by a new understanding followed by a new experiment, etc. until the *consistency* of the fundamental concept is established beyond doubt. This interplay between experiment and theory plays a very important part in great discoveries in physics. But they are two different things and one must recognise this. And one cannot live without the other. Theoretical physics cannot exist without experimental physics and experimental physics cannot exist without theoretical physics. The interplay must exist. Of course the story of the vacuum is just an example of what one gets into if one begins to think about the vacuum and fundamental physics, in general. I should be talking to you now about quarks, quasars and other odd species but one is inclined to go off at a tangent at a lecture like this with the consequence that little time is left for these topics. But I would not like to stop at this point without telling you how these ideas merge into a much deeper understanding of matter.

From the study of the vacuum of electrically charged particles arose the suggestion that vacuum structures, so established, are a general phenomenon of all charged particles, with charges now being other than electrical. In particular, if one were to pursue the substructure of atomic nuclei to the level of quarks, the well established constituents of nucleons, one encounters a new charge that these particles carry. But this charge is always neutralised - we only detect particles neutral under strong charge and quarks are not available to be looked at individually. Why?

While one tries to understand this, the only conceptual explanation that one arrives at is the fact that actually these particles live in a different vacuum. That is, the region of space inside nucleons in which quarks can live is, indeed, a different vacuum. But the substance around it is the kind of vacuum we live in. One usually

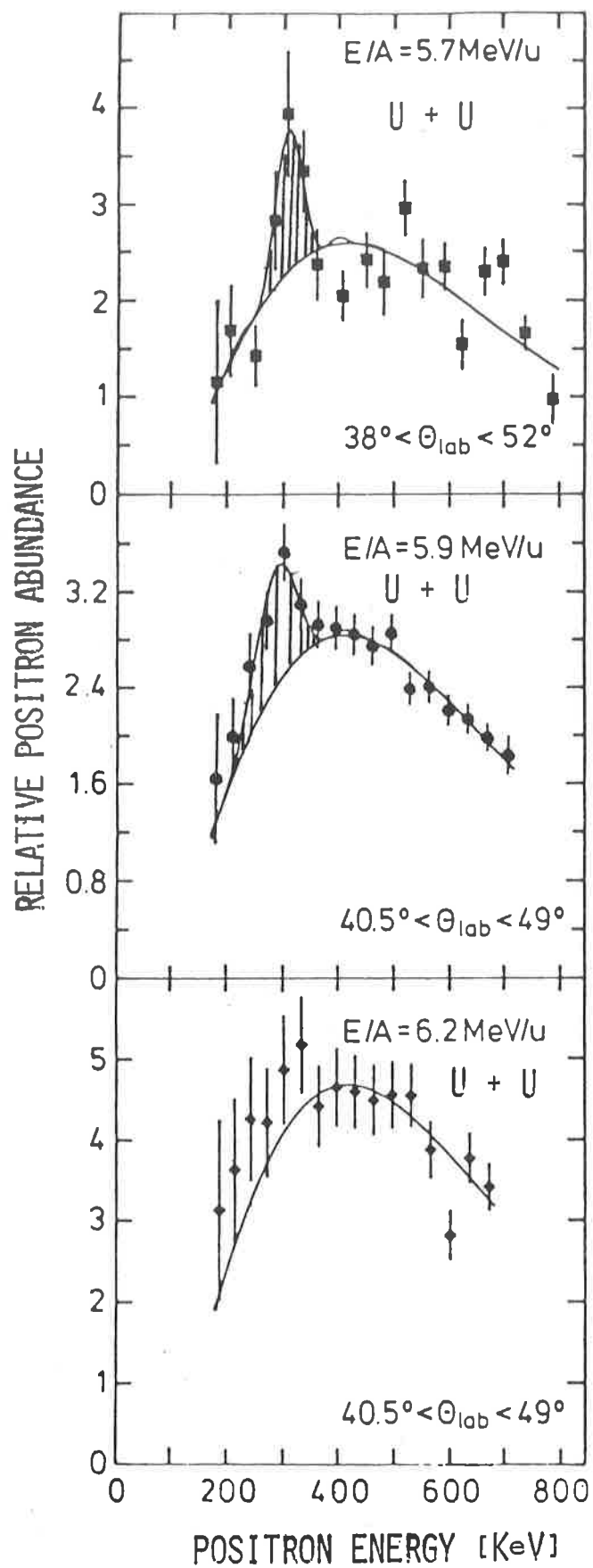


Figure 4 : Positrons from Vacuum Decay

calls this the true vacuum and the inside, the perturbative vacuum.

We have already accepted the concept that there can be different vacua. But here a step forward is made: two different vacua can coexist, they are here simultaneously, except that the perturbative inside vacuum is very small. Its region of space is very small compared to space domains we have experienced. The radius of a proton is of the order of 10^{-13} cm. Now arises the question: What do I do in order to create a large volume of this new vacuum? That is certainly the next step in order to test the consistency of the coexisting vacuum picture. I must be able to make a large box of perturbative vacuum - a box full of different nothing. And I will come to this point below.

But first we must understand why, in the first place, these different nothings only come in small sizes in nature. The answer is that it takes energy to change the structure of the vacuum. The inside is a different 'nothing', but it takes some form of energy in order to get there. This is our current understanding of what happens - we must *melt* the true vacuum. We must supply the energy and melt the ice - that is exactly what is needed in order to get to the new state. It is like what happens to water: you have two states - ice and water - they are two different structures of the same thing, exactly a parallel situation to our coexistent vacuum. We have true and perturbative vacua - both are just different structures of the 'nothing'. I have to supply energy in order to go from one to the other. So we must now accept that we live in an ice age! This ice age already exists for $1.5 \cdot 10^{10}$ years - the lifetime of our universe. The last heat period ceased 10^{-6} sec (one millionth of a second) after the birth of the universe, so we have only spent a short time in the other melted state. As the universe expanded, and temperatures dropped, the vacuum froze, leading ultimately to the present state of iced vacuum. Conceptually, this scenario is well understood, but since the birth of the universe has been a one time event, we do not have a firm experimental basis to confirm the above. While practically everybody in particle and theoretical physics believes in this picture, this belief in frozen vacuum picture is mainly supported by the fact that it is currently the only consistent explanation of all scarce experimental facts. But this hypothesis has until now not been subject to thorough experimental verification. And we recall that one negative experiment is sufficient to uproot the understanding. But there is at present no reason whatsoever for this picture of coexistent vacua not to be the correct one.

Today we can attempt to simulate the hot early universe by colliding matter - heavy nuclei - at high velocity. The heat generated may suffice to melt the vacuum locally and open the opportunity to study the fundamental degrees of freedom in the melted state. The concept of 'quark-gluon plasma' is so developed. Remember, however, that subnuclear particles are investigated. So the needed particle accelerators are giant and the experimental effort quite outrageous. Temperatures and pressures thousands of times higher than in the sun would be needed. Still, the programme in this research field is likely to proceed and be a fruitful one for all involved. Its particular importance is the undertaken test of the principle of true and perturbative vacua needed for the explanation of the elusiveness of quarks. But we should recognise that what we learn in such experiments will not only concern the past of the universe, but also its present structure. Extreme conditions are believed to prevail in the centres of very densely collapsed stars - neutron stars. It is possible that the interior of the star has 'melted'. Even more exciting is the possibility that the least understood of all stellar objects, quasars, may have an energy generating core consisting of melted vacuum.

Physics has led to great advances in our society, but these have usually lagged behind the fundamental developments by about 50 years, as the technology was refined to take advantage of new opportunities opened by new discoveries. Now

what fundamental which was discovered 50 years ago, begins to be useful today? Well if you look into the history of elementary particles, you will notice that 48 years ago the muon was discovered. What is a muon? It is a heavy brother or sister of an electron. It is 207 times heavier than an electron, otherwise it is exactly the same particle. And upon recognition of the discovery, quite a noted physicist said 'Who ordered that thing? What do we need it for?'

Actually, this is a very deep question, as with quantum mechanics: What is this thing doing here? Why is it there? This is a physical question - *the muon is there*. We have discovered it, so we have got to find at least one other experiment which needs muons to be consistent with the other known laws of physics. Muons must somehow intermesh with the rest of physics in order to keep the truth (nature) simple and beautiful. For 48 years nobody found a good reason. As we understand the world of elementary particles a little better today, I might say that we are perhaps further away from an understanding than we were, say 25 years ago. That is a big problem! But since 50 years have almost passed, we should ask: Is the muon useful? Yes, it is extremely useful today - and it is a very beautiful example of how many things work together in order to make a discovery useful.

The fact is that all energy problems on earth would be solved if we had means of generating energy by the fusion process, the same process that keeps the sun running. Now, pressures and temperatures in the sun are high and we do not yet have the technological means on earth to build similar circumstances. However, muons are catalysts of the fusion process. It is known that in chemistry, catalysts are important ingredients in many reactions. Many things can happen, but they take a thousand years to occur - you put in a catalyst and it happens very quickly. Muons are catalysts of the fusion process. And there is a catalytic chain when you put muons into a suitable mixture of light nuclear isotopes which will generate a lot of fusions. The full potential of this fact was not recognised for many years. Actually, the catalytic role of muons had been anticipated theoretically, and discovered experimentally in the fifties. But it was incorrectly concluded that the muon could only catalyse about one fusion, before disappearing in a radioactive decay. Muons have, unfortunately, the property that they decay after one millionth of a second. They have very short lives. So the point is that if you have an expansive catalyst, you want it to last a long time. But while it was found that the catalyst functions well, it could only last the time needed to catalyse about one reaction. And one fusion per muon is not an interesting enough proposition on how to approach our energy problems.

But in such circumstances, one must compare the time scales involved with each other. One must find out exactly what in the catalytic chain is so slow that you can have one fusion per muon. When this question has been posed, it seemed that nothing can be done to accelerate some of the involved nonactivated times. What has been ignored is the strong dependence on isotope composition, conditions such as temperature and pressure of the reaction chain. This arises as a consequence of miraculous accidents which make certain muonic molecules behave similarly to electronic molecules and to resonate with them. But when you have a big computer and understand the needed fundamental laws of physics, you can give answers to such questions. You can question if there is a way in which a muon can catalyse 300 fusions. Well, as it turns out, it appears that the answer is very likely yes. Actually, an interplay between theory and experiment has taken place here. First it was discovered (theoretically) that about three to ten fusions should be possible - and an experiment confirmed this. Then it was said that, after new data had been evaluated, there should be up to 100 fusions possible, if one does it correctly. Experiment confirmed this. It furthermore indicated that about 300 fusions are possible, that a muon can catalyse about 300 fusions before it dies or the catalyst is

poisoned by impurities. That of course means that we have quite a new avenue towards energy production based on particle physics and complex concepts of quantum mechanics, atomic physics and molecular physics, which could not be anticipated at all just six years ago.

We have been lucky - and essentially only because there is an exchange of ideas between theory and experiment. You learn about new results which, after some thinking, lead to new concepts and better understanding. One learns to do things better. It is the communication between theory and experiment which is very important. So allow me to conclude that since the implications of these advances on future energy generation are enormous, we may have found another good excuse to continue our fundamental research in physics for fifty more years! And I believe strongly that current work at the frontiers of science will benefit mankind, not only academically, though it is surely our curiosity that propels our work.

In closing this lecture, I would like to extend my acknowledgements to several people whose intellectual influence on me has been most profound. First, to my *father*, a lawyer and distinguished economist by profession, who has clearly recognised and strongly supported my interests in natural sciences. Then to my *wife*, a companion who not only has borne the strain of a scientist's life, but has often made an important contribution to it. Now, turning to my academic teachers - *W Greiner* has shown me the path to 'How' while *M Danos* led me on to 'Why'. But I would probably not be standing here today if it had not been for *JS De Wet*. I thank Jack most sincerely for bringing me to Cape Town, and I hope to be able to fulfil all his dreams.

Vote of thanks by JS DE WET, Professor Emeritus, UCT

I first of all want to answer Jan's question. He asked, 'Why do people do physics?' I would like to see the chap who stops Jan from doing physics. In fact, he does it because he cannot stop!

I would like to say a few words before I formally thank him for his really sparkling and inspiring address. Any university worth its salt and which has high academic aspirations must be extremely careful about the kind of people they appoint to their chairs. It is a very slippery slope. Once you start dropping standards in the appointments of your professors, before long, you are way down where you do not want to be. I would like, therefore, to spend a little time just to assess our new professor of theoretical physics.

These inaugural lectures have a very important function at the University. They are the shop window of the University. They put on display the newly appointed professors and give people a chance to look and see how they like them and to form judgements about them. I think, therefore, that it is a fair proposition to assess Jan on his performance this evening and on his past record. I want to do this.

But before we do this, let us try and put into perspective the importance of physics in the first place and then theoretical physics in the second place, in the hierarchy of the University, or if you like, in the hierarchy of the science faculty. Because as you may know, universities operate on the basis that all chairs are equal. Everything is always equal at the University, when money is distributed. Everybody must get the same share and it goes on and on like this. But in real life, all chairs are not equal, in fact some of them are significantly more equal than the others ... And I would like to say, first of all, that chairs in physics have a very special place in the science faculty, because physics is essentially the basic science. I like to think, and I often say, that all of science, all those components of science which are conventionally described as physics are, in fact, simply applied physics. So natural

science consists of physics and the rest of science which is applied physics. Brian Warner gave me a nice quotation this afternoon, something Rutherford once said: 'All science is either physics or butterfly collecting ...' Now I would not go quite as far as that. I would, however, defend to the death the proposition that these bits of science that are not physics, are simply applied physics. Everything derives from physics.

Now, where does theoretical physics fit into the scheme of things? I think Jan explained this to you. I was going to explain this to you at some length, but I won't do it anymore, because I think he has done such a splendid job in explaining that physics without theoretical physics around, would be pretty much of a dead duck before very long. Because it is the cooperation between theoreticians and experimentalists which really makes the subject an active one. I attended a seminar by Friedel Sellschop this afternoon at which he gave a very interesting talk about lots of things and what was a recurrent theme all along was, in fact, the interplay between the experimentalists and the theoreticians - how they work together and in order to have a flourishing and alive physics activity anywhere in the world, one needs, in fact, a team of first class theoreticians working with a team of first class experimentalists. Then you get going! So that, in a sense, none of science would really flourish without physics - and physics could not flourish with theoretical physicists. So really, theoretical physics takes prime place in my scheme of things. And therefore, the chair of theoretical physics at UCT is the most important chair in the University as far as I am concerned. That is a pretty clear statement.

Now, I want to see how we fared in appointing Jan Rafelski to this most important chair in our hierarchy. My verdict is quite simple! I think we have hit the jackpot! I want to tell you a little bit about what I think makes a good theoretical physicist - this is based on long experience in which I have met lots of people who are among the great theoretical physicists of our age. Let me mention a few names: Einstein, Dirac, Heisenberg, Schrödinger, Wolfgang Pauli - people like that. Eugene Wigner - I either worked with some of them or have been closely associated with others. What characterises all these people is, in fact, an almost uncanny physical intuition. One way or another, *they know how things work*. It is not logical thinking, just deep down within themselves, *they know how things work* and it is people of this kind who really make the grade. Now, I have seen perforce, quite a lot of Jan ever since he first came here 18 months ago. I have had plenty of opportunity to observe him and I am quite convinced that Jan has precisely that spark that has characterised some of the people I have known. I think particularly of RPF - whom I knew when he was barely out of short pants, in Princeton. Jan has many of the characteristics of RPF as a young man. And I am sure that he is going to go places in a big way, without any question whatsoever. Which all makes me a very happy man - because I can foresee a tremendous future for theoretical physics at UCT and in this country - And insofar as I have any power to help him realise this wonderful ambition *of his and mine*, for creating something of this kind, I will do all I can, and I am sure the University, which has already done a great deal to make this appointment possible, will also follow and do the same thing. So under all these circumstances, I think you will agree with me that, for me to be able to move a vote of thanks to Jan for his splendid lecture is a great pleasure indeed. I would like to do so now, Jan, Congratulations!

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