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"Welcome to 'IFL Science, The Big Questions.' The podcast where we invite the experts to explore the biggest mysteries of science, with your host, Dr. Alfredo Carpineti."

I: Look around you. Everything you see is made of matter. From the device you're listening to this episode on, to the furthest galaxies of the cosmos. But when we look at the physics, there is no clear reason why this should be the case. Matter has an equal and opposite alternative, called antimatter. Particles of antimatter have the same mass as matter, but an opposite charge. So why did the early universe favour one and not the other? We don't know, but we are about to find out… hopefully!

Welcome to a new episode of 'IFL Science, The Big Questions.' We are joined by Experimental Particle Physicist, Dr. Jeffrey Scott Hangst, who is a spokesperson of the Alpha Collaboration at CERN. The question we are going to explore today is, 'Why is the universe made of matter and not antimatter?'

Dr. Hangst, it is a pleasure having you with us. Can you tell us a little bit about yourself?

R: Yes okay, so I'm a Professor of Physics in the University of Aarhus in Denmark, but I spend all of my time in Geneva, because my main activity is the research on the Alpha Experiment, which has been going on for a long time now, we started in about 2006. We deal with antihydrogen and I guess we'll talk more about that. But Alpha is about 60 people, rather small experiment on the scale of CERN, but again we've been operating for a long time, we pre-date the LHC, you know, the big machine here, and it's a very interesting branch of Physics. Very different than the typical thing that goes on here at CERN. I'm an American but have been in Europe for 30 years or so. And my job is in Denmark, but I live in Geneva.

I: Can you tell us a little bit more about the Alpha Collaboration and what exactly you do, before we go into the matter of antimatter?

R: Sure. So, antimatter is this kind of mysterious substance that we all puzzle about, because it looks as if you could make a universe out of antimatter, but matter and antimatter don't exist in the same space, that's a very bad thing. They annihilate, or release lots of energy. But yet the particles of, you know, every particle that we know about that makes up the universe as we know it, has an equivalent antimatter particle. So, we're trying to study antimatter with a very high precision. And you might think you need a big machine like the LHC to do something like that, but it turns out the best way to get precision is to look at an atom of antimatter. So we work on the simplest possible antimatter atom, which is antihydrogen. So, hydrogen is number one on the periodic table, it's the most abundant element in the universe and here at CERN we're able to create the antimatter equivalent and then study it.

And this is an effort that has been going on for more than 30 years, to try and learn how to do this, to make antihydrogen to trap it, so that you can study it. But that's our main goal, we're asking a very fundamental question that the so-called 'Standard Model,' (you hear that term around all the time), this is our best understanding of how the universe is screwed together. It requires that hydrogen and antihydrogen behave in exactly the same way. So we went out to test that experimentally, with very high precision, to see if that's actually true. Maybe there's something we're missing here, right? Because the elephant in the room is always, 'Well why did the universe choose matter instead of antimatter?' And that's like, I'm sure that's your main interest in all of this, our interest is a little bit different, we want to really test the fundamental supposition that these two things are really equal, but opposite.

I: Thank you so much for that answer and we're going to get into the big question that is, 'why is the universe made of matter?' But first can we discuss a little bit about what we know already about antimatter and what else there is to know?

R: Sure. So, lets first understand what we think should be the case, which is that these fundamental particles, let's just take you and me, we're made of three things: protons, neutrons and electrons, right? That go into the atoms and make up our bodies and everything around us. Each one of those particles has a purported antiparticle, which has, we think, the same mass, but the opposite charge, right? And if we look deeper, the proton and neutron are made of quarks, the antiproton, antineutron will be made of antiquarks and these things when they get together, they annihilate they, you know, make this huge, microscopic explosion that leads to a lot of cool science fiction and we'll get into that later, if you want.

But experimentally, we have to verify all of this, right? So, does the antiproton really have exactly the same mass as the proton, right? Does the positron have exactly the same charge as the electron? Those are experimental questions that you can answer and you answer them with some uncertainty, right? There's always an uncertainty in the measurement, so you can ask, 'do the electron and positron have the same charge?' Typically, we measure the charge to mass ratio, so the charge divided by the mass. And then you can go and do an experiment with these particles are available in the lab and you can actually put an experimental limit on that. And when we talk about physical laws in science, we're talking about things we understand to the best ability we have to measure them, right? There are no real absolutes, you know? If in five years, we do a better measurement and find some deviation, then we have to address that. We can't just go off and conclude that these things are completely identical. And that's the theory, that's what the theory requires and guys like me, we test the theory.

So until very recently, the tests have been like that measure, compare a particle to its antiparticle, okay? So what's unique about our work is that we actually compare a composite thing, an atom that's composed of antimatter, compared to an atom of matter, right? So that puts even more constraints on it, because now you have the interaction between them and the internal structure of the hydrogen atom, which is something we've been studying for 200 years, right? To understand how atoms work and how they're linked together. So we're now able to delve into that with antimatter and that's really cool, to be able to do that, after all this time, actually measure the properties of an antimatter atom. And that's basically what I've dedicated my career to, which is getting to this point where we can actually compare these things and say, 'Wait, are they the same?' And how well do we know that they're the same?

I: **Absolutely fascinating and as far as we can tell, how close are the antihydrogen to regular hydrogen? Do the forces of the universe, lateral magnetism, gravity, affect them in different ways?**

R: Okay. That's a whole lot of questions right there [laughs]. The first thing that we're addressing mostly is the electromagnetism, because that's what holds atoms together, right? It's a positive and a negative charge that are attracted and make this bound state that we call an atom. Can we be a little bit quantitative? I mean, we're going to have to be, if you want to understand how well we know these things.

One reason that this is so compelling with antihydrogen is because we kind of think we understand everything about hydrogen right? That the first atom that was, you know, kind of studied, a Professor in Denmark, Niels Bohr, was the guy who made the first model of the hydrogen atom that we learned Quantum Theory and Atomic Physics by studying hydrogen essentially, right? And then later came Dirac and Quantum Electrodynamics and antimatter and so it's all nicely welded together in the matter sector. So the question is, how well do we measure those things first? How well do I actually understand hydrogen?

Now here's a simple experiment. Hydrogen, you know, the toy model for hydrogen, I have a nucleus and I have an electron going around it. And it has something called 'the ground state,' which is the lowest energy. And if I shine light on that hydrogen atom, I can jump that electron up, one quantum jump, from the first state to the second one, right? Like the most basic thing you could do to an atom is just excite the electron from one energy state to the next. That was the revolution when we understood that that was a discrete, you know, quantum jump, you have to have exactly the right energy to do that. And when it comes to light, that means exactly the right colour, okay? So if you want to go from one to two in hydrogen, you need exactly the right colour of light to shine on it and then it'll jump. That colour, we would translate to a frequency of the light, the electromagnetic radiation. And the reason I bring this up is that that's what we measure, when we're dealing with a laser that excites an atom, we're measuring the frequency of the electromagnetic radiation.

Okay, so lets talk about units, in frequency we measure in hertz, you know, just like your home stereo goes you know, 20 to 20,000 hertz, right? Cycles per second. The electromagnetic radiation that we're talking about with atoms has a frequency of one and fifteen zeros of hertz, okay? So that's a thousand, trillion hertz, okay? It's a big number. We can measure that number to plus or minus a couple of hertz, okay? So a few parts out of a thousand trillion. That's precision, right? If you want precise measurements, you go to Atomic Physics. These are the guys who know how to actually measure things, okay? So that's also, almost mind-boggling. It's like, you know, in the top five of the numbers that we know, right? That and how well we know them are things like this, okay? And another thing I should point out is, we measure that absolutely when we're talking about a hertz, we're talking about, you know, per second. So we need actually the definition of time, to go into that measurement.

And the measurements, the best measurements on hydrogen compare these kind of frequencies to the definition of time, right? Which is a standard you know, atomic clock. So this is serious measurement, we call Metrology. You know actually, what's the absolute scale of things that you know, we have to define to even make physics, how to be able to talk about time. Okay? So that's what's very unique about our measurements, is we're going to do, we do the same thing with antimatter. And so the people who have been studying that hydrogen line since the first time anybody held up a prism to the sun, right? And 200 years of this. So we know that really well. So all I have to do, all I have to do, is measure that in antihydrogen and compare the two. And then I have an incredibly precise comparison of, in this case, the electromagnetic behaviour of an anti-atom. So that's what motivates this. That's why you go to an atom, instead of just, you know, looking at a particle in an accelerator, or single particles, which can also be done very precisely right now.

But this is a kind of a, you know, higher level thing, because you're looking at the interactions between the two, also. Because we're looking for any evidence of completely new behaviour, right? That's the whole key, here. All the laws of physics that we understand, predict these things are exactly the same. So if there's any difference, there has to be something we haven't thought of and that's what drives us here, is that we know there's something wrong, with the, you know, with evolution of the universe and the matter and antimatter issue, but we haven't been able to identify what it is yet. So, our job here is to take a really close look.

Now you asked how well do we know that these two things are the same? So the hydrogen guys have 15 zeros when they measure. In antimatter now, we have 12 zeros as of 2018. And that was the last time we did the measurement. You may or may not know, CERN was kind of shut down for a couple of years, for upgrading. So, the last real measurements we did were in 2018. But I think we've shown that we're going to be able to do the same type of precision that they have in hydrogen. We had some really good developments at the end of 2018 and we're now just starting up again, to be able to measure again. So that's where we are now, with this particular comparison, hydrogen, antihydrogen.

You also asked about, you mentioned gravity. So the atomic physics, the spectroscopy, the lasers, the light, that's the easy, internal structure of antimatter atoms. The other really interesting question is, 'how does gravity affect antimatter?' So we live in a, as far as we know, the universe is made of matter, but now we finally have something where we could ask, 'what happens if I drop some antimatter in the gravitational field of the earth?' You might ask why haven't we already done that? We've had antimatter particles around a long time, right? We've been working with antiprotons since the 80's. Why haven't we done that? Or, positrons have been around for ever, why don't we know the answer to this? And that's because those particles are charged. And the electromagnetic interaction is much, much stronger than gravity.

Gravity is a really, really weak force. So, you know, you experience it if you fall down and break your collarbone. It's gravity that knocked you over, but it's electromagnetism that broke your collarbone, right? In the collision. So, gravity is a weak force and any experiment that you could imagine doing with a charged particle would be completely overwhelmed by the electromagnetic interaction. So you need something that's neutral. And that's what antihydrogen is. It's net neutral, it's an atom with no net charge. And it's also something that's stable, you know? You make it, we think it will just hang around for ever, as long as you keep it away from matter.

So, our second experiment which is, I just got off shift, I've been here since 7am. What we're doing right now is turning on, learning how to operate the experiment that we call 'Alpha G,' which is the experiment to see what happens if you drop some antihydrogen in the gravitational field of the earth. So there are two obvious questions, 'does it fall?' 'Is it repelled?' That's a little bit of science fiction, but there are some papers out there, where people say this would explain a lot of things, if it goes up. If it falls, does it fall at the same exact rate as matter, right? That's also an experimental question. And we're hoping to answer those questions in this machine, Alpha G. So, it was first installed right at the end of 2018, before CERN shut down and right now, it's in its first serious shakedown and hopefully we'll be able to do some physics before the end of this year. So very exciting, we have good success with the atom, the internal structure and now we're going to hopefully address the gravity , before too long.

Gravity is a big pain in modern physics, right? Because we understand general relativity, you know, motions of stars and black holes and… but there's not a quantum theory of gravity and we know everything else we have been able to quantise, with great success, but gravity is this outlier that really gives people headaches. And so it's kind of a no-brainer, if you have some antimatter and we are the ones who have it, you should drop it and see what happens. So it's a really exciting time. All this stuff has just come together in kind of the last five years, where we're able to, actually do all of these experiments.

I: **It is fantastic that we are hopefully at the edge of finding out some fundamental truths about why antimatter is not as abundant as matter.**

R: Yeah, I can't promise you to answer that question, I'm actually… I don't really care, you know? To me, it's… I have this stuff, I'm able to create it and hold onto it and so I'm going to study it. And let the chips fall however they do, this may or may not have anything at all to do with the predominance of matter in the universe. No one can predict this because don't have even a good theory or framework about that.

I: All right, so for our big question, what are the different avenues in which researchers around the world are trying to investigate this question? We mention studying the electromagnetic properties of antimatter, the gravity and what else is out there, trying to find an answer. Why the universe is made of matter and not antimatter?

R: Again, none of these are, you know, guaranteed to give you an answer, right? We like to liken this to a guy who has lost his car keys at night; so he looks under the streetlamp, not because his keys will be there, but because he can see, right? So, right now, that's exactly what we're doing, we're doing the experiments that we can do and maybe there'll be some connection, but there's no guarantee, or even a model.

The third thing that's maybe, a couple of things that are overlooked here, one is, at the LHC, you can go to the highest energy and maybe something new pops out, right? Maybe something that's completely unanticipated shows up because you're able to study an energy that's never been accessible before. So, in particular there's an experiment called 'LHCB,' that is really interested in the matter and antimatter symmetry, or asymmetry. And so they're studying that, at you know, the energy frontier, at the highest possible energy that's achievable. So far they haven't found any indications of new physics, but that's an obvious place to look, right? You look in the LHC, because we've never seen things that happen there before.

The other relevant experiment is that there is an experiment on the International Space Station, called 'The Alpha Mass Spectrometer.' And it's looking for antimatter that comes arriving from space. Now, there are some natural mechanisms to produce antimatter, you know? As long as there's high energy stuff out there, it can be produced in the same way that we produce it at CERN, by collisions with matter. So, there's not no antimatter in the universe, but it's, as far as we can tell, you know, it doesn't just hang around. It's only produced occasionally. So they're looking for any deviation that might indicate that there is some antimatter left over someplace.

You want to be, you know, really exaggerated, the universe is really big, right? And we haven't been exploring it for very long. What if the antimatter went off to the left, after the Big Bang, right? And we just haven't seen it, okay? That's kind of a ridiculous example, but we can't completely rule out that there isn't some antimatter out there, somewhere. So, that's why it's cool to go looking, in every way that we know how. I think that sort of covers the essence of what people are doing to try and address this. But there isn't a good theory, you know, to tell us where to look. We know there's a little bit of asymmetry, but it doesn't come anywhere near to giving us the universe that we have, right? The amount of asymmetry from the Big Bang. Because that's the issue. When energy at the beginning of the universe in the Big Bang, some of it went in to mass, right? $E=MC^2$, that's, Einstein tells us energy and mass are interchangeable. We use energy here in the lab, to make our antiprotons. The thing is, when we do that in the lab, we always get equal amounts of matter and antimatter and then as far as we know, that's a natural law. So that's the problem here. We simply don't know if there were equal amounts of matter and antimatter, what happened? Why did most of the matter survive? So, there's really not a good theory and that's why we look.

I: I think that is fantastic motivation to keep looking.

R: That's the way I put it. I mean, I can't make any kind of predictions that my measurements will be involved in this in any way. But it's clear this so-called baryonic symmetry, that's the technical term for it, that's what motivates us. We know there's something wrong and we have the best, most sensitive possible technique to look at this exotic stuff, so of course you have to do that, right? I mean, obviously.

I: Well, wonderful! And I wish you the best of luck to actually find that there's something absolutely wrong with our current laws of physics.

R: That would be cool. What I always say to people is that, you know, if that happens and we find a difference, that's amazing, if we don't find a difference, it's just as hard, to do the experiment and not so amazing. [Laughs]

I: **Thank you very much for taking the time to talk to us today.**

R: It's my pleasure. Okay, thank you very much.

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