High-Energy Physics: An Introduction

By Sharon Butler

This unofficial paper accompanies the OECD Global Science Forum's "Report of the Consultative Group on High-Energy Physics" which represents the consensus findings and conclusions of government-appointed delegates. The non-expert reader may wish to consult this introductory paper first, to become familiar with the basic concepts and terminology of high-energy physics.

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What is high-energy physics?

High-energy physics is the study of the smallest components of matter and how they interact. These fundamental particles are the stuff from which our entire world is made. Invisible to the naked eye – so tiny that the most powerful electron microscope can't see them – these particles, and only these, compose our homes, the cells of our bodies, and the warm rays of light on a summer's day. Some are not even particles of matter: they're bundles of pure energy. In studying them, high-energy physicists seek to learn what our world is made of, how it is put together, and how it works.

Remarkably, investigations into this inner space of our material world also reveal much about outer space. Approximately 15 billion years ago, right after the Big Bang, our universe was a chaotic, undifferentiated mix of fundamental particles. Galaxies, stars, planets – and eventually human beings, refrigerators, and mosquitoes – all emerged from these primary ingredients. When high-energy physicists create fundamental particles in the laboratory, they mimic conditions that existed billions of years ago in order to study how our universe began, how it has evolved, and even how it might end.

High-energy physicists hope to tell us not only how our world works, but why it is the way it is. If the fundamental particles had arranged themselves differently in the early stages of the universe – if, for example, there were a smaller proportion of carbon, sulphur, and other heavy elements – the phenomenon we call "life" would not be possible.

"Our universe, and the laws governing it, had to be (in a well-defined sense) rather special to allow our emergence," writes Sir Martin Rees, Britain's Astronomer Royal. In discovering what makes it special, high-energy physics may ultimately help us understand why we are here on Earth at all.

Current state of knowledge

Finding out what matter is made of is not an easy task. To understand how a car is designed, we simply take it apart – remove the engine, pull out the carburettor, etc. With particles, we can't do that, because any tool that we might use would itself be made of particles. The only way to disassemble matter is to hurl one particle into another, the equivalent of driving two cars into a head-on collision and examining the mangled fragments. In what were once called atom smashers and now are referred to as particle accelerators, particles are propelled to high speeds and high energies, and then slammed into one another to break them apart, and sometimes to create new ones. The higher the energy, the deeper we can probe into nature's smallest constituents.

Through such experiments, high-energy physicists have pieced together a theory of the basic structure of matter and its forces. According to this theory, called the Standard Model, the tremendous complexity of our world is built up from a remarkably small number of elementary particles.

At one time, scientists thought the smallest possible unit of matter was the atom. But experiments showed that the atom itself was made of electrons plus a nucleus containing protons and neutrons – and that protons and neutrons themselves break down into fundamental particles called quarks. According to the Standard Model, all matter is composed of two categories of elementary particles: quarks and leptons, six kinds of each.

These particles of matter interact through four fundamental forces of nature: gravity, electromagnetism, the strong force (which holds together the nucleus), and the weak force (which governs certain kinds of radioactive decay).

These forces are also composed of particles, called gauge bosons. One of these, the photon, transmits electromagnetism. The W and Z particles carry the weak force. (The Standard Model actually considers elecromagnetism and the weak force to be different aspects of one underlying “electroweak” force.) The gluon is responsible for the strong force. The graviton is presumed to carry gravity, but this particle has not yet been found and is not incorporated into the current theory.

The Standard Model has proved a triumph of modern science, with enormous explanatory and predictive power. The theory has made stunningly accurate predictions about certain behaviours of the fundamental particles, which many measurements have confirmed. The theory has even predicted the existence of particles that scientists had not yet observed – the top quark, for example – but were able to find by designing experiments based on theoretical calculations.

Areas of ongoing and future research

As successful as the Standard Model has been, it leaves open some fundamental questions. It doesn’t tell us, for example, why particles have mass – or why they have such different masses. Why should the top quark weigh as much as an atom of gold, while an electron weighs almost nothing?

The field of high-energy physics is at a crossroads. Experimental data, along with strong theoretical work, all suggest that we are on the verge of new insights that will take us well beyond today’s Standard Model. For the most part, these new insights are expected to emerge in experiments at energy levels that the next generation of accelerators will be able to reach, thanks to advancing technology.

Specifically, the Standard Model predicts the existence of a Higgs particle (named for the British theorist Peter Higgs), which would explain where the masses of particles of the electroweak force come from, and possibly even the masses of quarks and leptons. High-energy physicists believe they’ll find the Higgs when the Large Hadron Collider, now being built at CERN, begins operation. If they don’t find the particle, the Standard Model will certainly have to be revisited. If they do find it, the discovery will lead us into new territory: theoretical studies already suggest that the Higgs will be made of a new kind of matter, unlike the particles we know today.

Neutrinos are also part of the Standard Model. There are billions of them in every room of every house, yet they are so elusive they can fly through a wall of lead several light-years thick. According to the theory, neutrinos have no mass, but recent experiments have proved otherwise. That finding has now opened up a whole new arena to be explored – hinting, again, that the Standard Model needs modification.

In the next generation of experiments, high-energy physicists believe they'll find evidence of a unity underlying the Standard Model's diverse particles. We already know that the weak force and electromagnetism, two distinct forces in our everyday world, become one at higher energies. That discovery has led to speculation that other such "symmetries" exist. Supersymmetry theory, for example, claims there is a fundamental unity, or symmetry, between matter particles and force particles. If this is true, then every quark, lepton, and gauge boson should have a heavier partner particle. Particle physicists are intently searching for these "sparticles."

If high-energy physicists could peer still deeper, into nature's tiniest interactions, they believe that all four forces (gravity, electromagnetism, strong, weak) would become one. Like all of science, high-energy physics looks for the deep connections underlying the astounding diversity of our physical world. The simpler theory is considered to be the more elegant one – and it's usually the more accurate. Here again – aesthetically – the Standard Model fails to satisfy. Its framework doesn't even include gravity, which is better explained by the curvatures of spacetime posited in Einstein's general relativity theory. Is there a new theory, perhaps, that could supplant both?

Since the Standard Model does not account for gravity, high-energy physicists are developing other theories – string theory, brane theory, and theories of extra dimensions – to bring gravity into the fold. According to string theory, matter is ultimately made of tiny loops (strings) that vibrate at different frequencies. Different vibrations create a quark or a lepton, or even a gauge boson.

Like string theory, theories of branes and extra dimensions suggest that our universe contains many more dimensions than those we experience with our senses. This idea is already being tested in the laboratory. Future particle accelerators, while not powerful enough to directly penetrate the minuscule scales of these elusive dimensions, might enable us to see deeply enough into matter to witness the effects of such underlying features – the evidence of their existence.

Many of the questions high-energy physicists are exploring bear directly on the composition and evolution of our universe. Every type of particle of matter has a twin "antimatter" particle with the opposite electrical charge. Theoretically, matter and antimatter were created in equal amounts when the universe began, but today, matter predominates. What happened to the antimatter? Why aren't there antiplanets with antianimals? High-energy physicists are studying slight differences in the behaviour of matter and antimatter that might account for the way our universe evolved.

The universe is also apparently made of different *kinds* of matter. Astronomers have long known that besides the luminous matter we can see – like stars and planets – there is also dark matter. Its gravitational effects are evident in the distorted orbits of objects in outer space. But what is this substance that is estimated to make up as much as 90 percent of the matter in the universe? Candidates include the particles hypothesised in supersymmetry theory.

Dark *energy* is even more puzzling. Astronomical observations suggest that some force is causing our universe to expand at an ever-increasing rate even as dark matter pulls it back together. High-energy physicists are designing experiments to find out what this energy is.

The tools of high-energy physics

To study the fundamental particles of the physical world, high-energy physicists look to two sources: nature itself, and the laboratory.

Many experiments study naturally occurring particles, such as cosmic rays, a steady rain of high-energy particles originating in outer space, or neutrinos produced in nuclear reactions in the Sun. The Super-Kamiokande experiment in Japan, for example, studies neutrinos generated by cosmic rays using a detector that is 40 meters high and 40 meters in diameter, filled with 50,000 tons of purified water. The size is important because neutrinos rarely interact with each other or with anything else. The more material placed in their way, the more likely it is that one of these elusive particles will collide with another particle instead of just whizzing by. It is the collision that triggers detection.

In the laboratory, particle accelerators enable physicists to create abundant supplies of fundamental particles under controlled conditions. Designing, constructing, and operating these giant machines is costly, involving years of research and development and large, dedicated collaborations of scientists from numerous fields.

The highest-energy accelerators direct opposing beams of protons or electrons into head-on collisions to produce the desired fundamental particles. Powerful electrical fields inject energy into the beams, accelerating them until they are travelling almost as fast as light. Magnetic fields, created by standard and superconducting magnets, steer the beams and keep them tightly focused.

To observe the newly created particles, high-energy physicists use huge detectors with multiple layers of complex electronics that wrap around the collision point within the accelerator. Data from each layer, recording various properties of the emerging particles, reconstruct events taking place after each collision. The information is fed into computers and analysed.

The higher the energies accelerators can reach, the deeper physicists can pry into the structure of matter, and the farther back they can probe into the origins of the universe, to the mix of elementary particles that started it all. CERN’s Large Hadron Collider and the planned linear collider (both of which are discussed in detail in the OECD report) will achieve energy levels 10 times greater than any accelerator that now exists.

At these energy levels, physicists expect to fill in the gaps left by the Standard Model and move beyond its framework, testing whole new theories about the nature of matter and its forces.