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SYMMETRY BREAKING AND ASYMMETRY IN THE UNIVERSE

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The big bang theory postulates that all matter that currently exists in the universe was created at one moment, nearly 14 billion years ago, at the birth of the universe itself. All the fundamental particles we know, from the massive Higgs boson to the miniscule neutrino, were formed in that one moment. This primordial particle soup then interacted with itself and combined in various ways. Out of the primeval chaos emerged the universe we live in today.[1]

However, there is a nagging problem with this narrative: prima facie, the universe should have no reason to discriminate between matter and antimatter. Antimatter has all the exact properties of regular matter, with only the signs of its charges reversed. Why should the universe favor one over the other? And yet, if matter and antimatter had been created in exactly equal amounts, they would have precisely annihilated each other, leaving the universe full of energy from their explosive demise but nothing else—no atoms, no molecules, no stars and galaxies, and no us.[2]

Evidently, the clear symmetry between matter and antimatter, known as C symmetry, should result in a universe devoid of matter. But a quick glance at their surroundings should convince any skeptic that the universe is in fact not empty; moreover, it seems to have a great deal more matter in it than antimatter.

How do we explain this puzzling matter-antimatter asymmetry? The answer to this question lies, surprisingly, in the most fundamental symmetries of nature, leading science to question its long held beliefs about physical symmetry. It is in the universe's departure from perfect symmetry that we may find the answer to one of the most fundamental questions of them all—why do we exist in the first place?

SYMMETRIES IN PHYSICS

> *"How nice it would be if we could only get through into looking glass house! I'm sure it's got, oh, such beautiful things in it! Let's pretend there's a way of getting through into it, somehow."*
>
> *Through the Looking-Glass*, by Lewis Carroll

"The mirror world of classical physics was, in fact, once a fairly boring place, its monotone enforced by the principle of parity symmetry, which demands that the mirror world be exactly identical to the real one."

The story of matter-antimatter asymmetry begins with one of the most basic symmetries of nature: mirror symmetry. Our macroscopic world is in no way universally mirror symmetric. Most of the objects we see in everyday life would look very different through a mirror. Things

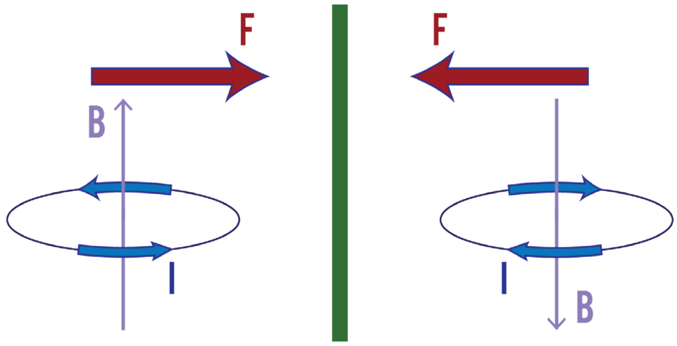

Figure 2: Magnetic field does depend on the left-right orientation of atomic currents. *B denotes the magnetic field created due to current flowing along the direction of I. A left-right reversal of the spin of the currents causes the magnetic field to flip from up to down. However, even in this case, while the magnetic field might gain an up-down flip which would cause its mirror image to appear different from itself, all its observable effects, such as the exerted force, are still flipped in the left-right direction only, preserving parity symmetry.*

get much more interesting (or much less interesting, depending on your point of view) when we analyze the basic phenomena of classical physics, such as fields and particle interactions. The mirror world of classical physics is governed by the principle of parity symmetry, which demands that the mirror world be exactly identical to the real one. To define it more formally, classical physics demands that a system be unchanged when the coordinate axes we use to measure it are reversed, which is called a parity transformation. Granted, what is right for a person is left for their mirror self, but the concept of left and right is itself a relative one, and without arbitrarily deciding on one direction as "right" or "left," there is no way we can differentiate between these two worlds. In this sense, all the laws of physics must work the same way in the mirrorscape as they do in "real" life. The mirror world (which is to say a "parity-transformed world") is no less "real" than the normal one we live in.

At least until the twentieth century, all of the known fundamental forces of nature were understood to be invariant under a mirror reflection. Gravity, for instance, would work the same way in a mirrored world as it does in ours. The force of gravity is entirely described by the relative orientations of the interacting bodies. It does not depend on any absolute sense of a left or right direction, and thus is unaffected by a parity transformation. The universal obedience of physical systems to the principle of parity symmetry would lead physicists to declare parity conservation to be a fundamental property of nature.

SYMMETRY BREAKING

While the principle of parity symmetry is an irontight rule in classical physics, quantum physics presents a whole new story. The development of quantum mechanics was motivated, after all, by a series of particle phenomena which threw a series of monkey wrenches into the exquisitely built structures of classical physics. In 1957, a stunning experiment by experimental physicist Chien-Shiung Wu at the University of Columbia showed that parity symmetry is, in fact, broken in the radioactive decay of particles, which is governed by the then newly-discovered weak nuclear force. Professor Wu and her group aligned the spin (and thus the "atomic currents" and individual magnetic fields) of supercooled cobalt nuclei along an external magnetic field, and found that when the nuclei decayed radioactively, they emitted electrons preferentially opposite to the direction of their magnetic field. Magnetic fields are produced by spinning currents as shown in Figure 2; therefore, if the axes of rotation of the currents were aligned vertically, a purely left-right reflection of the direction of their spin would cause the decay electrons to go up rather than down. The emission of electrons, as an effect of the weak nuclear force, is thus antiparallel to the magnetic field, which is in contrast to the observed effects of the magnetic field itself, which always appear at right angles to the field as discussed in the figure. This is significant, because if we have two mirror reflections of the Wu apparatus, we can tell which one is in the real world and which is in the mirrorscape! Even though observers in both worlds may agree that the current flows from left to right in their reference frames (due to lateral inversion), the left-right reflection does not affect the up-down orientation of the observers and thus there will be a glaring difference between the two worlds in the direction of motion of the electrons. In the real world we only see electrons going downwards for this orientation of currents, therefore the world where the electrons go up must be the mirror world. The weak nuclear force has thus given us a universal standard for left and right, and equally significantly, shattered one of the core beliefs of physics.[3,4]

Having been suddenly deprived of their anchor of parity symmetry, adrift physicists now searched for the correct law for the weak nuclear force. Fortunately, there seemed to be a solution ready at hand—scientists found that if the weak nuclear force acted on matter particles spinning one way, it would act on the corresponding antimatter particle spinning the opposite way. Back to the Wu experiment: if we take the mirror image of the experimental setup and replaced all the atoms with antimatter atoms, then it would again be impossible to differentiate between the two copies of the experiment. This new symmetry was dubbed "CP" symmetry, which is a combination of C symmetry ("charge conjugation" symmetry, which is to say replacing matter with antimatter), and P or parity symmetry.[3]

This solution, however, only held up for so long. In 1964, scientists James Cronin and Val Fitch at the Brookhaven National Laboratory experimentally confirmed a violation of CP symmetry in the weak nuclear force—which won them the Nobel Prize in 1980 and threw the question of symmetry conservation wide open.[5,6]

If the discovery of P-symmetry breaking taught physicists that nature differentiates between left and right, the discovery it led to, that of CP violation, led physicists to a much more surprising conclusion—the

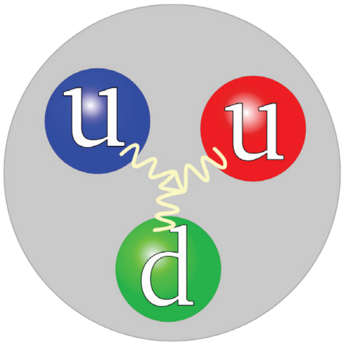

Figure 3: The quark structure of the proton.[13] *The proton is composed of three quarks bound by the strong nuclear force. The Strong CP problem refers to the strange lack of CP symmetry breaking in the strong nuclear force. There is no physical reason why the strong force would not show CP breaking, and its presence would go a long way in solving the matter-antimatter asymmetry puzzle. Observationally, however, not a single case of CP violation in the strong force has been found to this day.*

universe does discriminate between matter and antimatter. There exist nuclear reactions which produce more matter than antimatter, just as there exist reactions which produce particles of one spin more than particles of the opposite spin. This seems like exactly what was needed to solve the matter-antimatter asymmetry problem with the big bang theory. Sure enough, in 1966, physicist Andrei Sakharov proposed a recipe for a matter-antimatter asymmetrical big bang, establishing CP violation as an essential requirement to obtain a non-empty universe. The "Sakharov conditions" allow an eventual matter-antimatter asymmetry to arise out of a big bang where matter and antimatter particles were initially produced equally.[7,8]

Sakharov's conditions are but a set of requirements any theory of the formation of matter (baryogenesis) must fulfill, however. We are far from having solved the problem of matter antimatter asymmetry. In fact, one big problem physicists face today is to explain why there isn't enough asymmetry! For while Sakharov's conditions demand the existence of CP symmetry breaking to explain the existence of a matter dominated universe, none of the physical models we have today can provide enough symmetry breaking to account for the observed ratio between the amount of matter and antimatter.[9] This is known as the "strong CP problem." Finding new sources of CP symmetry violation is in fact a very active research field, with a CP breaking interaction being discovered in new particles as recently as 2019, which could possibly hint at a solution to this question. Matter antimatter asymmetry still remains a mystery though, and is considered one of the biggest unanswered questions of physics today.[10]

PERFECTION IN IMPERFECTION

Ancient natural philosophers were convinced that the heavens were absolute in their perfection. As long ago as the fourth century BC, Plato insisted that the celestial bodies were made in the most perfect and uniform shape.[11] Through the works of Kepler and Galileo, however, it was shown that the universe did not conform to humanity's conception of perfection. Planetary orbits were ellipses, not perfect circles. The other planets of the solar system had craters, "blemishes and scars," the same way the earth did.[12]

Perhaps our search for symmetries in the physical world is but an attempt to create order out of the apparent chaos we see around us. And yet, the most fundamental studies of reality have taught us that it is from the lack of symmetry, from the tiniest imperfection, that all that we see around us came to be. It is because the universe is just imperfect enough, that it is perfect for our existence.

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REFERENCES

1. The universe's primordial soup flowing at CERN. (2016, February 9). *Niels Bohr Institute*. Retrieved from https://phys.org/news/2016-02-universe-primordial-soup-cern.html
2. Garbrecht, B. (2018). Why is there more matter than antimatter? Calculational methods for leptogenesis and electroweak baryogenesis. arXiv preprint arXiv:1812.02651
3. Feynman, R., Leighton, R., & Sands, M. (1963). *The Feynman lectures on physics: volume 1.* (2nd ed.). Retrieved from http://www.feynmanlectures.caltech.edu/I_52.html
4. Garvey, G. T., & Seestrom, S. J. (1993). Parity violation in nuclear physics: signature of the weak force. *Los Alamos Science, 21.*
5. Christenson, J. H., Cronin, J. W., Fitch, V. L., Turlay, R. (1964). Evidence for the 2pi decay of the K20 meson. *Physical Review Letters, 13*(4), 138. doi: 10.1103/PhysRevLett.13.138
6. Gardner, S., & Shi, J. (2019). Patterns of CP violation from mirror symmetry breaking in the eta —>pi+pi-pi0 Dalitz plot. arXiv preprint arXiv:1903.11617
7. Balazs, C. (2014). Baryogenesis: A small review of the big picture. arXiv preprint arXiv:1411.3398.
8. Steigman, G., & Scherrer, R. J. (2018). Is The Universal Matter-Antimatter Asymmetry Fine Tuned? arXiv preprint arXiv:1801.10059
9. Mavromatos, N. E., & Sarkar, S. (2018). Spontaneous CPT Violation and Quantum Anomalies in a Model for Matter-Antimatter Asymmetry in the Cosmos. *Universe, 5*(1), 5. doi: 10.3390/universe5010005
10. LHCb collaboration. (2019). Observation of CP violation in charm decays. arXiv preprint arXiv:1903.08726
11. Zeyl, D., & Sattler, B. (2005). Plato's Timaeus. *The Stanford Encyclopedia of Philosophy*. Retrieved from https://plato.stanford.edu/archives/sum2019/entries/plato-timaeus/
12. Pasachoff, J. M., & Filippenko, A. (2013). *The Cosmos.* (4th ed.).Berkeley, CA: Cambridge University Press.

IMAGE REFERENCES

13. Rybak, J. (2018, January). *The quark structure of the proton* [digital image]. Retrieved from https://commons.wikimedia.org/wiki/File:Proton_quark_structure.svg