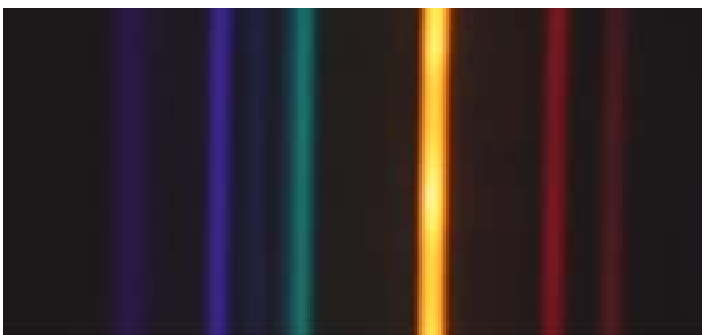
Helium:

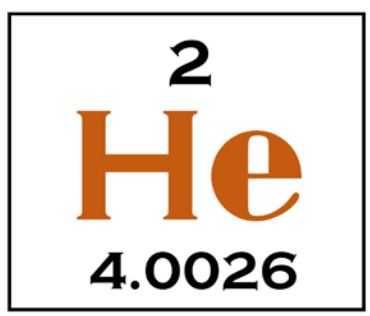
What is it?

Helium is an element named for Helios, the Greek Sun god. Its existence was proposed based on the study of the sun's chromosphere during an eclipse 30 years before its discovery on earth. In 1905, two University of Kansas professors, Dr. Hamilton Cady and Dr. David McFarland, succeeded in isolating helium from natural gas. They took a sample of natural gas "that would not burn" from Dexter, KS, removed the majority of the atmospheric gases by forcing them to stick to coconut charcoal, and then analyzed what gas remained by recording a spectrum. The spectrum, a fingerprint of elements that are present, showed that the remaining gas was helium—at a concentration of almost 2%.[1]



The spectrum of helium was used to first identify it on Earth[2].

Helium (abbreviated "He") is element number 2 on the periodic table of elements; only the element hydrogen has fewer protons. Two isotopes of helium are found in nature. Helium-3, with 2 protons and 1 neutron, is rare; a little more than one helium atom in a million is helium-3. By far, most helium exists as helium-4, with 2 protons and 2 neutrons.



Most helium in the *universe* is produced in large amounts through a "thermonuclear reaction" in stars, including our own sun. In the most common thermonuclear reaction that produces helium, deuterium (a hydrogen nucleus composed of one proton and one neutron, ${}^{2}_{1}\mathrm{H}$) and tritium (a different hydrogen nucleus composed of one proton and *two* neutrons, ${}^{3}_{1}\mathrm{H}$) collide with and stick to one another. The result is a helium-4 nucleus with two protons and two neutrons. The extra neutron does not incorporate and is released. The process in chemical notation is:

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}n$$

Think of the rule that "opposites attract" and "likes repel." Two positively charged nuclei will actually push away from one another. So how do we get nuclei to fuse at all?

In the interiors of stars, gravity squeezes elements close to one another. This poises them to fuse. What they need at that point is energy. The temperature in the interior of our own sun is about 15 *million* Kelvin (15 million degress Celcius or 27 million degress Fahrenheit[3].) This means the nuclei can collide at high speed and with great enough energy to overcome the repulsive forces between them. (They stay "glued" to one another due to the "strong nuclear force," which is stronger than the charge repulsion at very short—femtometer—distances.) High heat causing nuclei to combine is exactly what we mean by "thermonuclear" in this context.

The Milky Way is mostly hydrogen (74%), only about 24% helium, and very small amounts of other things[4]. This matches well and accounts for the composition of the sun and planets like Jupiter and Saturn, which have similar compositions.

But Earth doesn't have the gravity and temperatures necessary for thermonuclear chemistry. In fact, Earth doesn't even have enough gravity to retain *any* helium. Most of it floats up through the atmosphere and is lost to space. (Note the very small percentage on the poster—0.000008%[5]!) So how do we have any helium here on earth?

Most helium on *earth* is a different story. Helium here comes from nuclear fission—nuclei splitting apart into two or more pieces. The helium-4 nucleus—the atom without its two electrons—is generally called an "alpha particle" and can be denoted ${}^{4}_{2}\alpha$ or just α. Many elements will fall apart into a smaller, lighter nucleus and an alpha particle. Generally, the bigger the element, the more likely it is to decay and release alpha particles. Alpha decay is rare for lighter elements, although it does happen (for example, beryllium-8.) It becomes common for cerium (Ce, Z= 58) and elements beyond it in the periodic table. (This can be seen using an interactive periodic table) Thorium provides another, more commercially important, example of this decay:

$${}^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{88}\mathrm{Ra} + {}^{4}_{2}\alpha$$

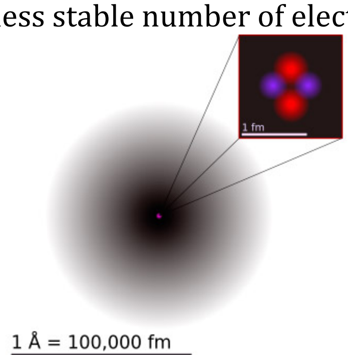
On its way out of the atom, the alpha particle can pluck off an electron or two from its parent nucleus. It can also remove an electron from atoms nearby. Generally, alpha particles don't travel very far, though, before they've collected two electrons to form a full helium atom. An "oxidizer" is anything that is good at removing nearby electrons, and the alpha particle is a *great* oxidizer, wreaking havoc on the immediate environment. For example, healthy living tissues have normal numbers of electrons until an α particle comes along. Stripped of their electrons, these tissues begin to function abnormally, which results in the symptoms of radiation poisoning.

Decay of heavy elements gives rise to the helium on Earth. Still, if helium evaporates away from the earth, shouldn't the concentration be *even closer* to zero? Generally, granitoid rocks that contain minerals rich in heavy elements like uranium and thorium are the sources of most terrestrial helium. Porous stone, like limestone, sitting above the granitoid rock, can then act as a storage tank[6]. This stone can then be mined for helium. (See the sections "How much do we have?" and "How quickly will it disappear?")

We've explained where the helium nucleus comes from—both cosmically and terrestrially. But why should this nucleus be surrounded by *two* electrons? Why not one? Three? Fifteen? None?

A simple answer would be "charge balance." To end up with an atom with no positive or negative charge (i.e., neutral), the number of electrons, each with a charge of -1, *must* equal the number of protons, each with a charge of +1. The nucleus, with 2 protons, has a charge of +2. Thus two electrons are required to cancel out this positive charge and make a neutral atom.

The more complicated answer is that the first two electrons of any element constitute a "complete shell." In a shell, electrons occupy similar regions of space, but in a way that they don't completely repel one another. Each electron is allowed to be in a certain volume within the atom. A property called "spin" allows electrons to exist in a similar, overlapping volume of the atom. This paired arrangement that fills the very first electron shell makes N=2 electrons very stable. More (3+) or fewer (1) electrons is a generally less stable number of electrons.



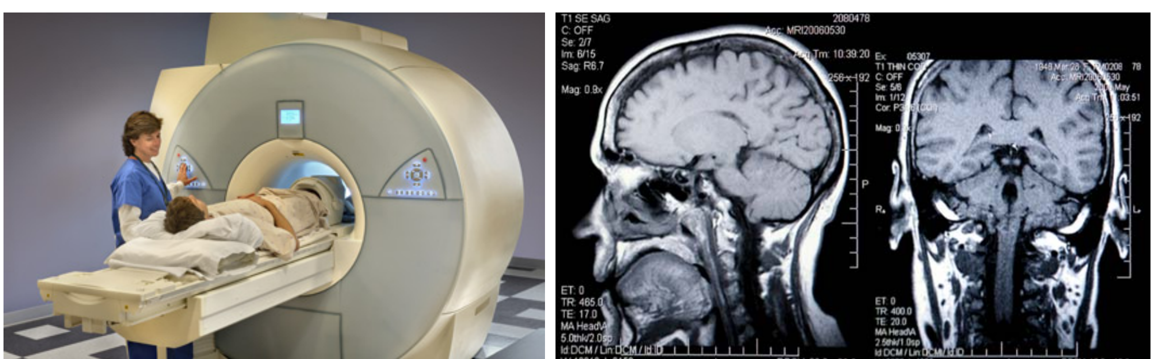
A concept of the helium atom. The nucleus, with two protons and two neutrons, is shown with an inset. The electrons are in the region surrounding the nucleus. The darker the area, the more like it is an electron is there[7].

Why and How is it useful?

Of all the elements, helium has the lowest boiling point—4 Kelvin!—which means liquid helium can be used as a highly effective coolant to achieve very low temperatures. Generally, substances with low boiling points have a very low mass. This is due largely to the fact that lighter materials have fewer electrons. The more electrons there are in an atom or molecule, the more that atom or molecule can interact with its neighboring atoms or molecules, using something called dispersion interactions (also often called "van der Waal's forces.") Dispersion interactions hold different particles close to one another, as in a liquid. Helium has only two electrons, so a helium atom is only very weakly glued to its neighbors. Only the slightest amount of heat will send a helium atom in a liquid flying off into the surroundings as a gas. The next highest boiling point is that of hydrogen (H_2)—around 20 Kelvin—followed by that of neon (Ne)—27 Kelvin[8]. While these are also cold temperatures, experiments that require VERY cold temperatures often start by cooling using liquid helium, particularly for magnetic, superconductive, or Bose-Einstein condensate experiments or devices. (See "Why and how is it useful?" above.)

Medical MRI Machines

Any instrument with a superconductive magnet needs to be cold. Superconductors are materials that conduct electricity without any resistance, generally below a certain temperature[9]. Importantly, curling electrical wires generates magnetic fields, so superconducting wires are important for any application involving a high-powered magnet. One example is "Magnetic Resonance Imaging," more commonly known as MRI, the medical technique that allows doctors to see inside their patients. In an MRI machine, the wires are coiled around the person, which is why the machine is shaped like a tube. This arrangement generates a strong magnetic field in the patient. The magnetic field in turn orients the hydrogen nuclei in the patient in a specific way that can be picked up with a pulse of light. The light is then converted into an image of the insides of the patient. This is only possible, however, with a strong current generating a strong magnetic field. See Gould & Edmonds[10] for an in-depth explanation.

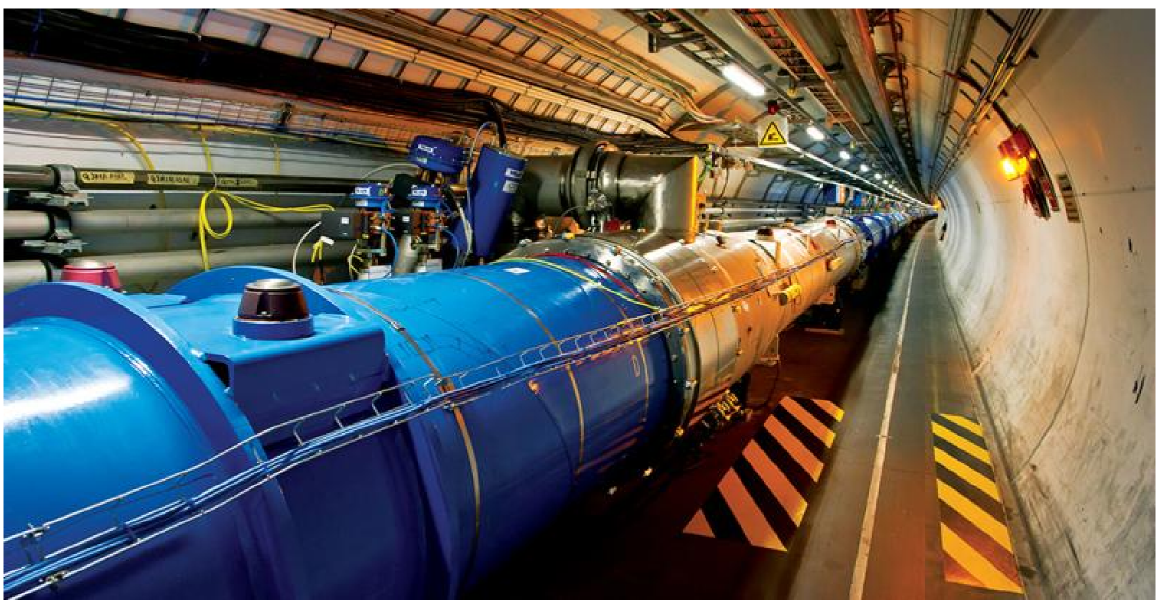


MRI machines, left[10], that depend on liquid helium provide physicians and inside look at their patients, right[11].

Different materials can be used for the wires in an MRI machine, but they only function as superconductors at very low temperature. Some of these materials and temperatures are niobium-titanium (NbTi, 9.4 K) and niobium-tin (Nb_3Sn, 18 K). Magnesium diboride (MgB_2, 30 K) is also being explored due to its higher superconductive temperature[12]. It might use other elements, like neon, as a coolant. Each MRI machine requires about 1,700 L of liquid helium to keep the wires around 4 K, well below their superconducting temperatures. New ways of cooling to low temperatures—requiring only a fraction of the helium—are now being explored. This may help slow the global rate of helium use[13].

Large Hadron Collider

The Large Hadron Collider (LHC) at CERN also uses liquid helium for cooling purposes. The LHC made headlines a few years ago for facilitating the discovery of the Higgs Boson or "the God particle." The Collider does just that—it focuses beams of charged particles with very high velocities to smash into one another. The beams of particles are brought into defined paths using very high strength magnets that are again based on superconducting wires. Cooling the wires below the superconducting temperature requires liquid helium. In this case, though, the instrument uses 130 metric *tons* of it[14]. Additional information about the instrument and associated discoveries can be found on the LHC website[15].



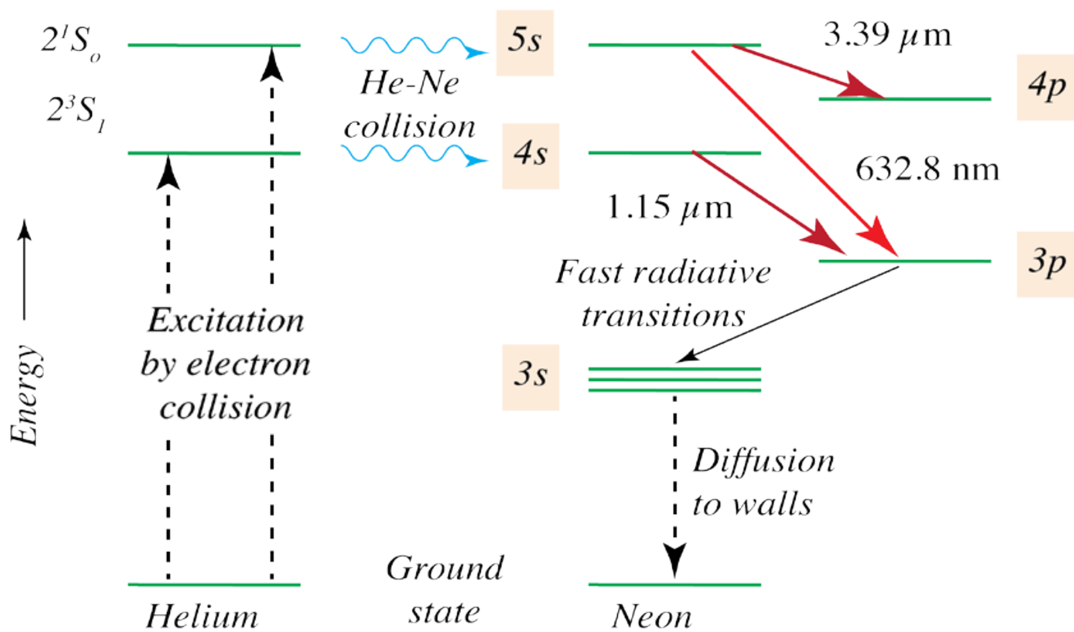
The Large Hadron Collider (LHC) uses 130 (metric) tons of helium[15]. Scientists used the LHC to detect the Higgs Boson, the most recently discovered subatomic particle.

Barcode Readers

Helium atoms to generate the red laser light used in barcode readers[16].

A final use for helium worth mentioning is in ubiquitous barcode readers. Barcode readers are used for identification in such applications as ownership and lending (as in libraries), recognition and tabulation (as in grocery and other stores), and recognition and sequential processing (as in mass transit and shipping like UPS or airport baggage checks.)

The laser generated by a barcode reader is actually produced using helium and neon atoms. A mixture of about 85% He and 15% Ne is placed in a thing tube. Electricity is then passed through the tube. This puts some of the helium atoms in an excited state, in which one of their electrons has additional energy beyond a normal (or "ground state") electron. Such excited helium atoms are in constant motion in the tube, along with the other helium and neon atoms. When an excited helium atom collides with a neon atom, it transfers its energy to the neon. The result is a neon atom in *its* excited state. The neon atom can shed some or all of this energy by emitting light of different wavelengths. The most common light emitted has a wavelength of 632.8 nm, making it red in color. Other possible wavelengths and colors include 612 nm (orange), 594 nm (yellow), or 543.5 (green)[17]. The process is shown schematically below[18].



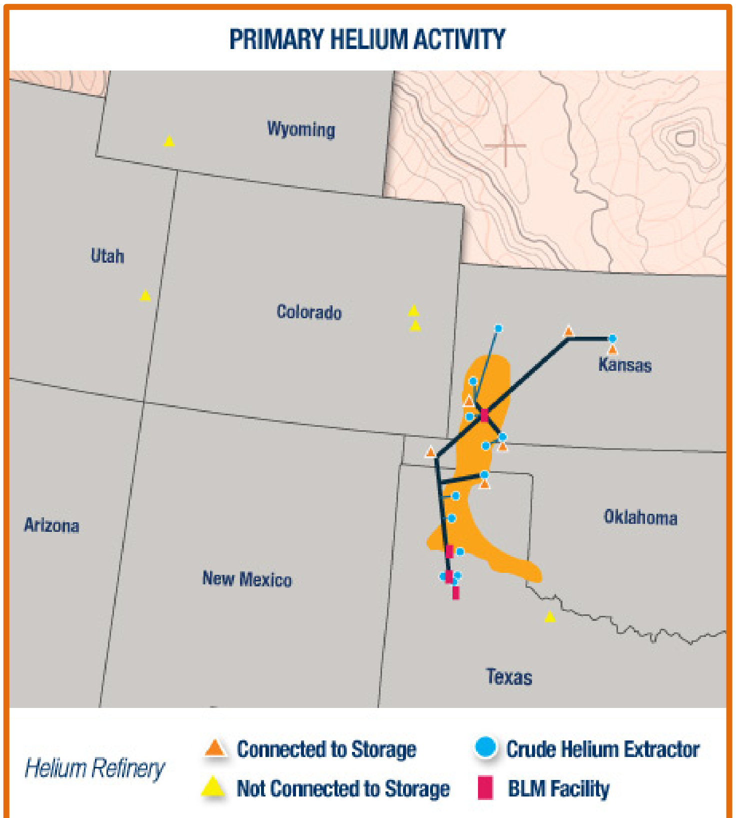
Excited helium atoms transfer their energy to neon atoms. Neon atoms with an electron in a 5s orbital can lose the energy an end in a 3p orbital. The lost energy leaves as a photon with a wavelength of 633 nm—red light [18].

How much do we have?
How quickly will it disappear?

No one knows exactly how much helium there is on Earth. It is certain, however, that there are at least a few billion cubic meters (3×10^9 m^3) [5]. This translates to around (5×10^8 kg) He. Global demand is around 30,000 (metric) tons or (3×10^7 kg/yr) ; this demand increases each year. Based on this, we would anticipate that we have another ((5×10^8 kg) ÷ (3×10^7 kg/yr) ≈ 16 years, meaning helium supply runs out in 2033. This is in excellent agreement with statements elsewhere[6] that indicate our helium runs out in 2030.

Solutions to the helium shortage problem include *making* more or *finding* more. Making more helium is not feasible due to the extreme conditions required. (See "What is it?" above.) Finding more may defer the run-out date.

Where do we get helium now? Where should we be looking for the next large helium well? About half the supply of the world's helium was recently (2016)[19,20] discovered in the African Rift Valley, most of which occurs in Tanzania. Another 30% of the world's supply comes from the North American Plains. Texas, Oklahoma, and Kansas are particularly rich in helium[21]. Kansas, is running short, with helium supplies lasting until around 2020[22]. Helium on earth was first discovered in Dexter, Kansas in 1903[23], making the 2020 date particularly interesting. The reserves will be depleted within about 130 years from discovery to exhaustion—a blink of geologic time. Replenishing such a reserve requires hundreds of millions to billions of years.



Most helium in North America is found on the Central Plains in TX, OK, and KS[21].

The formation of a helium deposit appears to be rare, requiring that several very specific conditions be met. Heavier elements that radioactively decay to produce helium (see "What is it?") are often found in core, mantle, and deep crustal rock. Rock formed from volcanic activity (i.e., igneous rock) can contain high levels of elements such as uranium and thorium. Derived rock types like sedimentary shales can also contain high levels of heavy radioactive elements and serve as the source of a helium well[24]. This rock must 1) be buried deep in the continental crust and 2) the patch of continental crust must persist for hundreds of millions of years or more without being subducted. 3) It must also then be covered by a capping material that can trap and store helium. Generally, high-density sedimentary rocks are appropriate for this purpose. 4) Then there must be some upheaval event that cracks the crust and releases the helium into the sedimentary "storage tank."[6] Because of these gold-locks conditions, discovery of new helium wells tends to be rare.

Regrettably, there are no perfect substitutes for helium. This is largely due to helium's peculiar physical properties. These properties arise from its low mass and full electron shell (See "What is it?"). What we can do is to change existing technologies that are based on helium. Two examples are using magnesium diboride (MgB_2) in superconductors or using helium in smaller amounts with newer cooling methods. (See "Medical MRI Machines.") An alternative, but currently technologically infeasible, way to maintain helium reserves would be capture it from where reserves run high—elsewhere in the solar system.

Summary / TLDR:

Helium—element number 2 with its unique properties—is rare and nonrenewable. Moreover, scanners, medical imaging, and scientific discovery—linchpins of modern society—all place high demand on supply. Scientific breakthroughs that include 1) discovery of new helium reserves and 2) alternative technologies that decrease helium use will both be critical in ensuring there is helium on earth for generations to come.

Appendix

Atomic Spectra. The collection and analysis of the spectra of elements is commonly used to identify different elements, or to determine the elemental composition of species made up of a variety of elements. The principles governing this technique rely on the fact that each element has distinct electronic energy levels that can be accessed by adding energy (typically using heat or an electrical current) to the element. For example, at ambient conditions, the two electrons of the helium atom reside in the lowest-energy 1s atomic orbital. This particular configuration (or arrangement) of electrons is referred to as the ground state of helium. The addition of energy to helium can excite these electrons to a higher-energy orbital, such as the 2s orbital, creating an excited state with a new configuration. This excited state is unstable, and can decay to the ground state by releasing energy in the form of a photon of light. Using simple mathematical relationships, the wavelength of the light emitted can be converted to an energy, which is the energy difference between the ground and excited state. Upon introducing a significant amount of energy, multiple excited states are populated, and relaxation from these excited states gives rise to emission of several photons of different wavelengths (the lines in the atomic spectra).

The energy separation between ground and excited states depends on several factors, including the nuclear charge, making the energies sensitive to changes in atomic number. Because of this, each atom shows a distinct set of atomic lines, resembling a finger print for that particular atom.

Femtometer. When thinking of atoms, one must consider tremendously short length scales. A femtometer is 10^{-15} meters. To put this value into context, the smallest item visible to humans is just under a millimeter (10^{-4} meters). The diameter of blood cells are on the order of 10^{-6} meters (micrometers), and the width of double-stranded DNA is on the order of 10^{-9} meters (nanometers). Consider how astonishingly small DNA is, and then ponder the femtometer, which is a million-fold smaller still.

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