Isotopes of helium

Although there are eight known isotopes of **helium** (**He**) (standard atomic mass: 4.002602(2) u), only helium-3 (3He) and helium-4 (4He) are stable. All radioisotopes are short-lived, the longest-lived being ^{6}He with a half-life of 806.7 milliseconds. The least stable is 5He, with a half-life of 7.6×10^{-22} seconds, although it is possible that 2He has an even shorter half-life.

In the Earth's atmosphere, there is one 3He atom for every million 4He atoms.[1] However, helium is unusual in that its isotopic abundance varies greatly depending on its origin. In the interstellar medium, the proportion of 3He is around a hundred times higher.[2] Rocks from the Earth's crust have isotope ratios varying by as much as a factor of ten; this is used in geology to investigate the origin of rocks and the composition of the Earth's mantle.[3] The different formation processes of the two stable isotopes of helium produce the differing isotope abundances.

Equal mixtures of liquid 3He and 4He below 0.8 K will separate into two immiscible phases due to their dissimilarity (they follow different quantum statistics: 4He atoms are bosons while 3He atoms are fermions).[4] Dilution refrigerators take advantage of the immiscibility of these two isotopes to achieve temperatures of a few millikelvins.

Helium-2 (diproton)

Helium-2 or 2He, also known as a diproton, is an extremely unstable isotope of helium, which consists of two protons without any neutrons. According to theoretical calculations it would have been much more stable (although still beta decaying to deuterium) had the strong force been 2% greater.[5] Its instability is due to spin-spin interactions in the nuclear force, and the Pauli exclusion principle, which forces the two protons to have anti-aligned spins and gives the diproton a negative binding energy.[6]

There may have been observations of 2He. In 2000, physicists first observed a new type of radioactive decay in which a nucleus emits two protons at once - perhaps a 2He nucleus.[7][8] The team led by Alfredo Galindo-Uribarri of the Oak Ridge National Laboratory announced that the discovery will help scientists understand the strong nuclear force and provide fresh insights into the creation of elements inside stars. Galindo-Uribarri and co-workers chose an isotope of neon with an energy structure that prevents it from emitting protons one at a time. This means that the two protons are ejected simultaneously. The team fired a beam of fluorine ions at a proton-rich target to produce 18Ne, which then decays into oxygen and two protons. Any protons ejected from the target itself were identified by their characteristic energies. There are two ways in which the two-proton emission may proceed. The neon nucleus might eject a 'diproton'—a pair of protons bound together as a 2He nucleus—which then decays into separate protons. Alternatively, the protons may be emitted separately but at the same time—so-called 'democratic decay'. The experiment was not sensitive enough to establish which of these two processes was taking place.

The best evidence of 2He was found in 2008 at the Istituto Nazionale di Fisica Nucleare, in Italy.[9][10] A beam of 20Ne ions was collided into a foil of beryllium. In this collision some of the neon ended up as 18Ne nuclei. These same nuclei then collided with a foil of lead. The second collision had the effect of exciting the 18Ne nucleus into a highly unstable condition. As in the earlier experiment at Oak Ridge, the 18Ne nucleus decayed into an 16O nucleus, plus two protons detected exiting from the same direction. The new experiment showed that the two protons were initially ejected together, correlated in a quasibound ^{1}S configuration, before decaying into separate protons much less than a billionth of a second later.

Also, at RIKEN in Japan and JINR in Dubna, Russia, during productions of 5He with collisions between a beam of 6He nuclei and a cryogenic hydrogen target, it was discovered that the 6He nucleus can donate all four of its neutrons to the hydrogen. This leaves two spare protons that may be simultaneously ejected from the target as a 2He nucleus, which quickly decays into two protons. A similar reaction has also been observed from 8He nuclei colliding with hydrogen.

$^{2}\mathrm{He}$ is an intermediate in the first step of the proton-proton chain reaction. The first step of the proton-proton chain reaction is a two-stage process; first, two protons fuse to form a diproton:

$$^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{2}_{2}\mathrm{He}$$

followed by the immediate beta-plus decay of the diproton to deuterium:

$$^{2}_{2}\mathrm{He} \rightarrow ^{2}_{1}\mathrm{D} + e^{+} + \nu_{e}$$

with the overall formula:

$$^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{2}_{1}\mathrm{D} + e^{+} + \nu_{e} + 042\ \mathrm{MeV}$$

Bradford has considered the hypothetical effect of this isotope on Big Bang and stellar nucleosynthesis.[5]

Helium-3

There is only a trace amount (0.000137%) of $^{3}\mathrm{He}$ on Earth, primarily present since the formation of the Earth, although some falls to Earth trapped in cosmic dust.[3] Trace amounts are also produced by the beta decay of tritium.[11] In stars, however, $^{3}\mathrm{He}$ is more abundant, a product of nuclear fusion. Extraplanetary material, such as lunar and asteroid regolith, has trace amounts of $^{3}\mathrm{He}$ from bombardment with solar wind.

For helium-3 to form a superfluid, it must be cooled to a temperature of 0.0025 K, or almost a thousand times lower than helium-4 (2.17 K). This difference is explained by quantum statistics, since helium-3 atoms are fermions while helium-4 atoms are bosons which condense to a superfluid more easily.

Helium-4

The most common isotope, $^{4}\mathrm{He}$, is produced on Earth by alpha decay of heavier radioactive elements; the alpha particles that emerge are fully ionized $^{4}\mathrm{He}$ nuclei. $^{4}\mathrm{He}$ is an unusually stable nucleus because its nucleons are arranged into complete shells. It was also formed in enormous quantities during Big Bang nucleosynthesis.

Terrestrial helium consists almost exclusively (99.99986%) of this isotope. Its boiling point of 4.2 K is the lowest of any known substance. When cooled further to 2.17 K, it transforms to a unique superfluid state of zero viscosity. It solidifies only at pressures above 25 atmospheres, where its melting point is 0.95 K.

Heavier helium isotopes

Although all heavier helium isotopes decay with a half-life of less than one second, researchers have created new isotopes through particle accelerator collisions to create unusual atomic nuclei for elements such as helium, lithium and nitrogen. The unusual nuclear structures of such isotopes may offer insight into the isolated properties of neutrons.

The shortest-lived isotope is helium-5 with a half-life of 7.6×10^{-22} second. Helium-6 decays by emitting a beta particle and has a half-life of 0.8 second. Helium-7 also emits a beta particle as well as a gamma ray. The most widely-studied heavy helium isotope is helium-8. This isotope, as well as helium-6, are thought to consist of a normal helium-4 nucleus surrounded by a neutron "halo" (containing two neutrons in $^{6}\mathrm{He}$ and four neutrons in $^{8}\mathrm{He}$). Halo nuclei have become an area of intense research. Isotopes up to helium-10, with two protons and eight neutrons, have been confirmed. Helium-7 and helium-8 are hyperfragments that are created in certain nuclear reactions. $^{10}\mathrm{He}$, despite being a doubly magic isotope, has a very short half-life.[12]

Table

nuclide symbol	Z(p)	N(n)	isotopic mass (u)	half-life	decay mode(s)[13]	daughter isotope(s)[14]	nuclear spin	representative isotopic composition (mole fraction)	range of natural variation (mole fraction)
2He[15]	2	0	2	?	p (>99.99%)	2 1H	0+(#)		
					β^+ (<0.01%)	2H			
3He[16]	2	1	3.0160293191(26)	**Stable**[17]			1/2+	$1.34(3)\times10^{-6}$	4.6×10^{-10}-4.1×10^{-5}
4He[16]	2	2	4.00260325415(6)	**Stable**			0+	0.99999866(3)	0.999959-1
5He	2	3	5.01222(5)	$700(30)\times10^{-24}$ s	n	**4He**	3/2-		
6He[18]	2	4	6.0188891(8)	806.7(15) ms	β^- (99.99%)	**6Li**	0+		
					β^-, fission (2.8×10^{-4}%)	**4He**, **2H**			
7He	2	5	7.028021(18)	$2.9(5)\times10^{-21}$ s [159(28) keV]	n	6He	(3/2)-		
8He[19]	2	6	8.033922(7)	119.0(15) ms	β^- (83.1%)	8Li	0+		
					β^-,n (16.0%)	**7Li**			
					β^-, fission (.09%)	5He, 3H			
9He	2	7	9.04395(3)	$7(4)\times10^{-21}$ s	n	8He	1/2(-#)		
10He	2	8	10.05240(8)	$2.7(18)\times10^{-21}$ s	2n	8He	0+		

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[13] http://www.nucleonica.net/unc.aspx
[14] Bold for stable isotopes
[15] Intermediate in the proton-proton chain reaction
[16] Produced during Big bang nucleosynthesis
[17] This and ^{1}H are the only stable nuclides with more protons than neutrons
[18] Has 2 halo neutrons
[19] Has 4 halo neutrons

Notes

- The isotopic composition refers to that in air.
- The precision of the isotope abundances and atomic mass is limited through variations. The given ranges should be applicable to any normal terrestrial material.
- Geologically exceptional samples are known in which the isotopic composition lies outside the reported range. The uncertainty in the atomic mass may exceed the stated value for such specimens.
- Values marked # are not purely derived from experimental data, but at least partly from systematic trends. Spins with weak assignment arguments are enclosed in parentheses.
- Uncertainties are given in concise form in parentheses after the corresponding last digits. Uncertainty values denote one standard deviation, except isotopic composition and standard atomic mass from IUPAC which use expanded uncertainties.

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External links

- General Tables (http://www.tunl.duke.edu/nucldata/General_Tables/General_Tables.shtml) — abstracts for helium and other exotic light nuclei

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