The Story of Gold

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Introduction

Throughout history mankind has sought gold for its corrosion resistance, malleable nature, and its beauty. The rarity of the metal made it valuable and much effort would be expended to secure supplies. It's not until recent decades that we have been able to gauge to rarity of gold in the Universe as a whole and attempt to explain why this is so.

Data published at WebElements [5] indicate that in the Earth's crust there is an average of 0.3 gold atoms for every billion atoms. For scale compare that to the abundance of oxygen, the most abundant element in the crust, at 600,000,000 atoms per billion. Outside Earth gold is less rare, with 700,000 atoms per billion in the Sun and 800,000 per billion as an average over a wide area of the universe. However, compared to the most abundant element, hydrogen at 930,000,000 atoms per billion, gold is still very rare indeed. In general, the heavier the element the less of it there is around. To understand why gold (and other heavy elements) are rare requires a look at where and how it is formed.

The nature of elements stems from the internal structure of their atoms. Each atom consists of a heavy nucleus surrounded by a cloud of lightweight, negatively charged particles called electrons. The nucleus contains two types of sub-atomic particles, protons (positive charge) and neutrons (no charge), bound together, against electric repulsion between protons, by the strong nuclear force. The number of protons in the nucleus, the atomic number, determines the element. The total number of neutrons and protons in the nucleus determines the atomic mass number. Differing numbers of neutrons in a nucleus creates variants of the atom called isotopes. Isotopes can be unstable, likely to spontaneously emit radiation or other particles, in which case they are called radio-isotopes. The time it takes for half of a sample of an isotope to decay is called the half-life and is a measure of the stability of the isotope. To identify atoms and isotopes scientists use a set of shorthand symbols: $^{12}_{6}C$. The subscript is the atomic number (6), the superscript is

the atomic mass number (12), and the letter identifies the element (in this case carbon).

Gold (Au) has atomic number 79. The only stable isotope has atomic mass number 197, 118 neutrons in the nucleus: $^{197}_{79}$Au. Gold has five radio-isotopes all of which have a half-life measured in days: $^{194}_{79}$Au, $^{195}_{79}$Au, $^{196}_{79}$Au, $^{198}_{79}$Au, and $^{199}_{79}$Au.

Current theories of the origin of the Universe dictate that only hydrogen and helium ($^{1}_{1}$H and $^{4}_{2}$He) were in existence shortly after the 'Big Bang'. From these beginnings there are a number of processes that combine to synthesise heavy elements from the primordial hydrogen. All of these processes are associated with stars.

To obtain elements heavier than hydrogen requires a mechanism to add protons and neutrons to the nuclei of the atoms. Under normal circumstances the positive charges in the nuclei of adjacent atoms repel each other and the nuclei do not come to together. However, deep in the core of a star temperatures and pressures are extremely high and nuclei are traveling fast enough that a small proportion of them overcome this repulsion, collide, and merge. This merging process is called nuclear fusion and through a chain of such merges new elements are born within stars. The most basic of these chains is called the proton-proton chain and results in the conversion of four hydrogen nuclei (bare protons) into a helium nucleus, a few light sub-atomic particles, and energy. This, and slightly more complex chains with the same result, are the only processes occurring early in a star's life.

Stars go through a series of life stages, each producing heavier elements, governed mainly by the amount of hydrogen they started with. In the red giant phase, helium accumulating in the core from hydrogen fusion has forced hydrogen fusion into a shell around the core. If sufficient mass exists then this helium core will eventually begin fusion into carbon, oxygen and neon isotopes, putting the star in the horizontal branch phase of life. As helium fusion products accumulate the the star enters a cyclical phase of life; each fusion cycle deposits fuel for a subsequent cycle in the core that, if sufficient mass is present, will ignite as lighter fuels are exhausted in the shell surrounding the core. Fusion of carbon leads to isotopes of oxygen, neon, sodium, and magnesium while the later oxygen fusion phase produces silicon, phosphorus, and sulphur. This cyclical phase of the star's life is called the asymptotic giant branch. Stars up to 4 solar masses, $4M_\odot$, go through to an asymptotic giant phase but never achieve sufficient temperature or pressure in the carbon core to ignite further fusion. Between $4M_\odot$ and $8M_\odot$ carbon burning is the last stage of fusion. Beyond $8M_\odot$ fusion of oxygen and heavier materials an occur.

Nuclear fusion seems to be the mechanism that will allow us build gold from hydrogen through a long series of nuclear fusion reactions. Unfortunately, there are two factors working against achieving this. Nuclear fusion requires getting nuclei close enough together that the strong nuclear force

can overwhelm electrical repulsion. The higher the proton count of the nuclei involved in a collision the larger the electrical repulsion that must be overcome. Consequently, the required temperature and pressures increase with nuclear charge, and only stars with sufficient mass to generate these conditions will sustain fusion. The second difficulty arises in stars with sufficient mass to create iron ($_{26}$Fe) isotopes. Fusion involving iron requires an input of energy because of this nucleus' inherent stability. Reactions that release energy are far more likely to occur, and fusion products arising from any rare iron fusion events are quite likely to spontaneously decompose into lighter elements. Stellar fusion creates all the elements up to iron but cannot continue on to produce gold ($_{79}$Au) because of fundamental limits to the fusion process.

Another way that changes to atomic nuclei can be effected without having to overcome the electrical repulsion of protons is called neutron capture. Neutrons have no electrical charge and therefore are much easier to introduce into a nucleus than protons or larger nuclei. Adding a neutron to a nucleus makes a heavier isotope of the same element and opens a path to other elements. For example:

$$^{58}_{26}\text{Fe} + ^{1}_{0}\text{n} \rightarrow ^{59}_{26}\text{Fe}$$
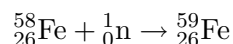
In most cases the heavier isotope is unstable and will decay through one of several mechanisms to a more stable state. Of interest is β^- decay because it leads to a new element with a higher atomic number. In β^- decay the nucleus emits a β particle (an electron) and a neutron becomes a proton. The resulting nucleus has one more proton than the original. For example iron becomes cobalt:

$$^{59}_{26}\text{Fe} \rightarrow ^{59}_{27}\text{Co} + e^-$$
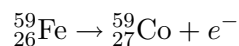
Through repeated neutron capture and β^- decay an atom can climb to higher atomic numbers. This process competes with the forms of decay that lead to lower atomic numbers. These forms of decay are (briefly): β^+ emission (positron emission, $^{125}_{57}\text{La} \rightarrow ^{125}_{56}\text{Ba} + e^+$), electron capture ($^{55}_{26}\text{Fe} + e^- \rightarrow ^{55}_{25}\text{Mn}$), and α decay in elements with 83 or more protons ($^{208}_{84}\text{Po} \rightarrow ^{204}_{82}\text{Pb} + ^{4}_{2}\text{He}$).

Neutron capture works from a base of pre-existing nuclei, particularly iron. These nuclei may have been manufactured in the star itself or they may be trace elements incorporated into the star from previous stellar generations. The neutron capture process in stars can occur slowly (s-process) or rapidly (r-process) depending on the abundance of free neutrons available to be absorbed. The two processes occur in different stellar environments and result in different nuclei.

The s-process is thought to occur primarily in asymptotic giant branch stars with a carbon-oxygen core. Such stars sustain the main neutron yielding reactions [1]: $^{13}_{6}\text{C} + ^{4}_{2}\text{He} \rightarrow ^{16}_{8}\text{O} + n$ and $^{22}_{10}\text{Ne} + ^{4}_{2}\text{He} \rightarrow ^{25}_{12}\text{Mg} + n$. Estimates

of the time between chance captures in this environment are in the order of hundreds to thousands of years [4]. The long period between captures ensures that any unstable isotope created by a capture event has time to decay until a stable isotope results. Over this period of the star's life traces of stable isotopes of elements as heavy as lead and bismuth ($^{208}_{82}$Pb and $^{209}_{83}$Bi) can be created. The limit around lead and bismuth exists because heavier isotopes are sufficiently unstable that they α decay into a lesser element. The s-process products from these stars are ejected as solar wind or in the more spectacular ejection of bulk mass to form a planetary nebula. Achieving gold through the s-process requires that stable isotopes of all the lighter elements have been achieved first. Of all the possible isotopes created by neutron capture, only a percentage will β^- decay into a stable isotope of a new element. Consequently, the cumulative likelihood of reaching a certain element decreases as the proton count increases. Gold is near the top of the s-process product chain and is therefore a comparatively rare output.

The s-process produces traces of gold but there is another phase of stellar life that can produce gold through neutron bombardment at a rate suitable for the r-process. In stars that are more than eight times as massive as the Sun ($> 8M_\odot$) the last substantial phase of fusion reactions involve the fusion of silicon ($^{28}_{14}$Si) into a range of elements clustered around iron ($^{56}_{26}$Fe). These reactions release energetic photons sufficiently powerful to tear apart nuclei that the star has spent a lifetime creating, a process called photo-disintegration. Photo-disintegration reduces large nuclei to much smaller nuclei and, in the process, liberates subatomic components including neutrons. The rate at which neutron capture can occur is dramatically increased and now outstrips the decay rate of very heavy isotopes. A new range of neutron rich nuclei is created and, although the process is balanced somewhat by photo-disintegration, in the regions surrounding the central core heavier isotopes may remain intact. Unlike the s-process these isotopes may be quite unstable and are sustained by constant bombardment.

The onset of photo-disintegration marks the beginning of the end for these stars. The forced fission of nuclei removes immense amounts of energy from the core of the star. The core can no longer support itself and collapses under the influence of gravity until fundamental forces between neutrons halt the decline abruptly. The ensuing shock wave propagates out through the inward falling outer layers of the star causing immense heating, fusion, and other nuclear reactions. The result is an intensely bright explosion, called a Type II supernova, that ejects the bulk of the star's mass into interstellar space at great speed. The r-process synthesis of heavy elements ceases as the star's gaseous envelope expands and thins. The ejected stellar gases now contains the huge range of heavy isotopes, both stable and unstable, that were present at the cessation of rapid neutron capture. The explosion distributes fusion and neutron capture products, including gold, across an immense area. This material is now available for incorporation

into future star generations. The heavier elements will form the seeds for neutron capture in new stars as well as for the formation of planets such as Earth.

Gold is not produced in quantity in stars too light to reach the carbon-oxygen core fusion stage. The neutron capture processes rely on a chain of random events to build base nuclei up to gold. For stars heavy enough to sustain neutron capture but not heavy enough to reach supernova stage only the s-process operates with the weak distribution of products through solar winds. Stars heavy enough to reach supernova stage produce a larger array of heavy elements and distribute them widely in the explosion. Supernovae, though, are rare events with only a handful expected in an average galaxy each century. The end result of combining these factors is that gold is relatively uncommon.

References

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