How reliable is AI?

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Supplementary information 2: Manually selected sources

Q1: Why don't radioactive decay chains end with iron?

The best answer is a combination from two sources, starting with Nicolau Saker Neto's reply to a similar (but oppositely-phrased) question on chemistry.stackexchange, which can be read in full at https://chemistry.stackexchange.com/questions/42922/why-do-all-radioactive-decay-series-terminate-at-lead.

"There are four main decay chains for actinides and superheavy elements. This is a simple consequence of the fact that one of the main processes to increase a heavy nucleus' stability is the emission of alpha particles, which have a mass number of 4 (42α); notice that if you take the isotope's mass number and divide it by 4, the remainder of this division (0, 1, 2 or 3, corresponding to the 4n, 4n+1, 4n+2 and 4n+3 mass number decay chains respectively) stays constant under alpha, beta or gamma decay. There are decays which change the remainder (neutron emission, proton emission, spontaneous fission, etc) and therefore allow hopping between the main decay chains, but for simplicity these can be approximately ignored for the isotopes which are not too unstable or too heavy.

Only three out of these four main decay chains "stop" at lead, so already the statement in the question is incorrect. The 4n, 4n+2 and 4n+3 chains "stop" at Pb-208, Pb-206 and Pb-207, respectively. The 4n+1 decay chain reaches Pb-209, but this lead isotope is quite short-lived ($t_{1/2}$=3.25 h) and decays further to Bi-209 where it "stops" (or at least seemed to until 2003).

Note that I said the chains "stopped" at these isotopes. In reality they don't. It just happens that Pb-208, Bi-209, Pb-206 and Pb-207 are all very long-lived isotopes, with half-lives billions of times greater than the current age of the Universe. This means that any continued decay is severely bottlenecked at these points, so for almost all practical purposes, the decay chains stop there. However, rigorously speaking, if you were really patient there would be further decays in the sequence. In fact, theoretically the heaviest isotope which is not susceptible to any known mode of spontaneous radioactive decay (except proton decay) is an isotope of zirconium, Zr-92, so the decay chains actually go on well past lead or bismuth. It just takes an immense amount of time for the decays to happen."

The second part comes from AXensen, who identifies as a PhD student in the physics program at University of California, Berkeley, working for the ALPHA experiment at CERN studying antihydrogen. The response came in answer to a question on physics.stackexchange about whether all elements heavier than iron will eventually decay to iron, available in full at https://physics.stackexchange.com/questions/803817/is-there-proof-for-elements-heavier-than-iron-will-decay-to-iron-by-processes.

"Just because iron has the lowest mass per nucleon does not imply that everything heavier than iron can decay to it. It is possible that an isotope has less binding energy per nucleon than iron, but the other particle (take alpha for example) it would have to emit to emit to reach iron has more mass than the difference between iron's mass and our isotope's mass. Notice that unless you're splitting into two irons, the other thing you're emitting also has less binding energy per nucleon than iron, so when you include both decay products it's not completely obvious that that end product will always be lower total mass.

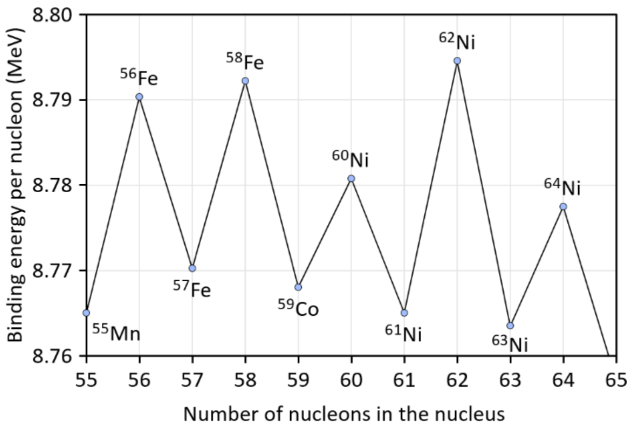
For example, Nickel 60 has a mass of 59.93079AMU, iron 56 (lowest mass per nucleon) has a mass of 55.93494AMU, and helium 4 has a mass of 4.00260AMU. Helium plus iron is more than nickel by 0.00675AMU. It will never decay in this way. And any other manner of decaying you might imagine would be much worse.

This is why there are stable isotopes above iron."

Q2: Which isotope has the highest binding energy?

This question contains a deliberate ambiguity: is it referring to the highest binding energy for the entire nucleus or the highest binding energy per nucleon? Both variants are covered in an outstanding explanation by Christopher Baird of West Texas University, USA. The full article is available at https://www.wtamu.edu/~cbaird/sq/2024/07/23/what-is-the-most-stable-nucleus/.

"The most stable atomic nucleus is nickel-62 in its ground state. This is because nickel-62 has the highest binding energy per nucleon of any type of nucleus. There are 28 protons and 34 neutrons in a nickel-62 nucleus, for a total of 62 nucleons. Books and websites often say that iron is the most stable nucleus, but this is simply not true.



Although it's a close call, nickel-62 has a slightly higher binding energy per nucleon than iron-58 and iron-56, as can be seen in the plot below." *(shown here above)*

"So why do books and websites say that iron has the most stable nucleus? There's two reasons. First of all, iron is far more abundant in the universe than nickel. The complex chains of nuclear reactions that occur in stars end up making far more iron-56 than nickel-62. You could therefore correctly say that iron-56 has the most stable nucleus out of all of the abundant elements.

Secondly, iron-56 has the lowest mass per nucleon out of all possible types of nuclei. This means that all sequences of nuclear reaction chains ultimately drive every other type of nucleus to become iron-56. That's why high-mass stars eventually end up with a core that is mostly made of iron, not nickel. Note that a nucleus's "binding energy per nucleon" and "mass per nucleon" are not exactly the same thing. Binding energy per nucleon determines the stability of a nucleus. The nuclide with the highest binding energy per nucleon is the most stable one, which is nickel-62. At the same time, mass per nucleon determines the ultimate end products of sequences of nuclear reaction chains. Iron-56 has the lowest mass per nucleon and is therefore the ultimate end product of nuclear reaction chains. It's possible for the ranking of nuclides by binding energy per nucleon to be slightly different from the ranking of nuclides by mass per nucleon. This is because a proton has a lightly different mass from a neutron."