comment

The most boring chemical element

Could it be boron or bohrium that is the most boring? You'll need to read to the end to find out.

Rebecca E. Jelley and Allan G. Blackman

It is the International Year of the Periodic Table (#IYPT2019), and one of us (A.G.B.) has been investigating the 118 known chemical elements as part of a series of short podcasts[1]. This process has highlighted the fact that every element, no matter how abundant or obscure, has its own story — the discovery, history, uses and quirks of each chemical element are unique. But let's face it, some elements undoubtedly have better stories than others, and this made us think about which one is the most boring. In order to answer this question, one must first define just what is meant by 'boring', something which we will attempt to do below. Although our analysis is based on facts, the final conclusion is merely our personal opinion; if fans of a particular element are in any way offended, they are free to write a response.

The Oxford English Dictionary, seemingly the ultimate repository for all matters of spelling and meaning in the non-American English-speaking part of the world, defines[2] the word 'boring' as 'That annoys, wearies, or causes ennui', which is really no help. Quite apart from the fact that there appears to be a missing 'which' prior to the word 'annoy' in the definition, the first thing you have to do is look up 'ennui' to find out what that means ('the feeling of mental weariness and dissatisfaction produced by want of occupation, or by lack of interest in present surroundings or employments', in case you're interested). So, what does 'boring' mean in the context of this article? Well, for an element to be boring in our view, it has to have a lack of interesting features. For example, phosphorus can't be classified as boring because it spontaneously bursts into flame in air. Similarly, uranium isn't boring because the ^{235}U isotope is fissionable. And in no way could fluorine possibly be boring, mostly because its elemental form reacts with pretty much every other element on the periodic table. Hopefully you get the picture.

The most boring element will be the one devoid of such redeeming features as those outlined above — we're looking for an element that essentially acts as no more than a placeholder on the periodic table. Before we embark on our search, we first need to remove some elements from contention. Simply by virtue of the fact that many of the transuranium elements have only been prepared in small quantities (in many cases, literally a few atoms) and that, consequently, we don't know much about them, we're going to exclude all elements with an atomic number greater than 92. This decision is, of course, entirely arbitrary and, in fact, one could quite reasonably argue that all these excluded elements are not even close to being boring because they have all been prepared by humankind — a quite remarkable achievement when you think about it.

And so, the search begins.

Let's begin by asking the question 'What makes an element interesting?' We would contend that factors such as great abundance or great scarcity are interesting properties. Why, for example, are nearly 90% of all the atoms in the universe hydrogen atoms? Or, why are francium and astatine the rarest naturally-occurring elements on Earth? So, chances are we're going to be looking for an element of which there's not too much, but not too little. However, such an argument might not necessarily apply when we're looking at the types of elements on the periodic table — given that roughly three quarters of the elements are metals, our most boring element could well come from these, rather than the less abundant (and henceforth more interesting) metalloids and non-metals.

Extremes of reactivity will also probably come into play; elements like fluorine, which are very reactive, or the noble gases, which aren't, are surely interesting. Physical properties will certainly play a part; we can straight away say that bromine and mercury cannot be boring because they are the only elements that are liquid at the temperatures and pressures typical in most sea-level locations here on Earth. Helium can't be solidified at atmospheric pressure, gallium exists as a liquid over a range of 2,373 °C (the largest of any element), osmium has the greatest density of any element at ambient conditions, and the list goes on. There seems to be something at least a little interesting about all elements, so you can doubtless see our dilemma and the reason why our final conclusion is going to be somewhat subjective.

A quick data-driven appraisal

How do we identify the most boring element? Well, we happened upon the easiest method without too much discussion — simply go to SciFinder, type in the name of each element under 'Explore: References: Research Topic', and note the numbers of references containing the term as entered. Armed with these data (Fig. 1), we could make this a very short article and proclaim that because francium has the fewest number of hits, it must be the most boring element. However, we've already highlighted that francium is inherently interesting because of its scarcity.

So perhaps mere numbers don't tell the whole story, although one of us (R.E.J.), being an organic chemist, is adamant that the numbers show carbon in its rightful position. Also, we suspect that SciFinder cannot distinguish between the elemental noun and the verb form of the word 'lead', because we were somewhat surprised to see this element feature in the top ten. Likewise, we only searched for the element names, and so species such as 'chloride' and 'bromide' won't register. Given these shortcomings, perhaps a more nuanced approach is required if we are to obtain a sensible answer to the question of which element is the most boring.

A systematic study

Let's see if we can identify candidates for the title of most boring chemical element by going through the periodic table group by group.

Group 1: H, Li, Na, K, Rb, Cs, Fr. We've already noted that hydrogen is interesting owing to its great abundance and francium is interesting for entirely the opposite reason, so they're out. Caesium is a metal that will melt in your hand (at around 28 °C), but don't try this at home because the moisture in your hand will ensure you receive substantial burns. So, not only is it almost the third liquid element under ambient conditions, but the fact that the Americans and the rest of the world can't agree about its spelling, makes it interesting enough to disqualify it. The first Bose–Einstein condensate (1995) consisted of a few thousand ^{87}Rb atoms and won its

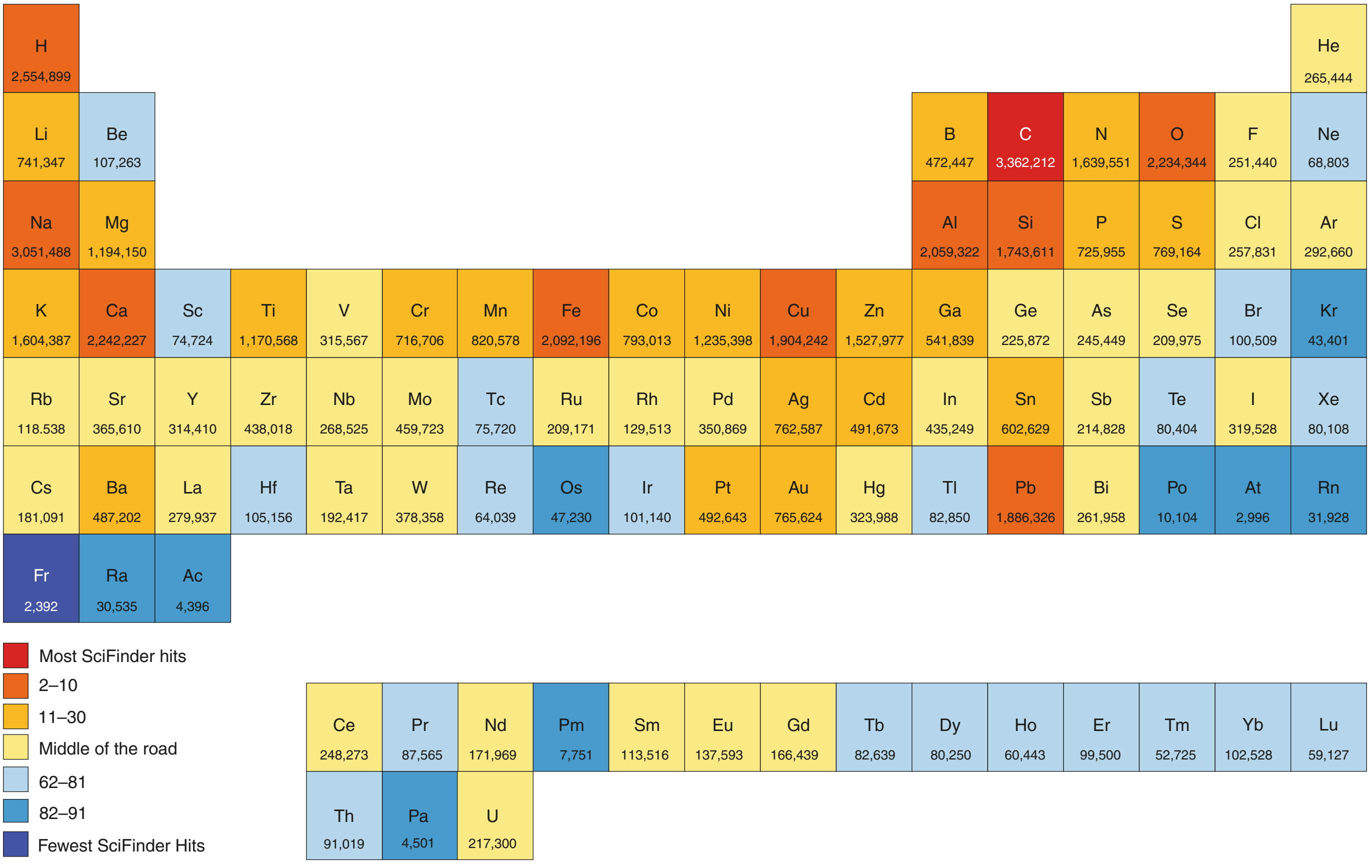


Fig. 1 | The first 92 elements, with the number of SciFinder hits as of 17 April 2019. Colour-coding is used to emphasise the different ranges of hits, red/orange elements having the most and blue elements the fewest.

discoverers a Nobel Prize two years later, making rubidium far too interesting for us[3]. Lithium is the lightest metal, whereas both sodium and potassium ions are rather important for maintaining a separation of charge across cell membranes, thereby facilitating the transmission of nerve signals. It looks as though there are no particularly boring candidates in group 1.

Group 2: Be, Mg Ca, Sr, Ba, Ra. The first element that can safely be discarded from group 2 is radium — although it's hardly the most useful element on the periodic table, what chemist doesn't know the story[4] of the Curies' herculean isolation of radium from pitchblende? The toxicity of beryllium, together with its presence in precious stones such as emeralds and aquamarine, mark it as an interesting element, while both magnesium and calcium are essential elements for humans, meaning we can forget them. That leaves strontium and barium, but barium is saved by its presence in the compound $YBa_2Cu_3O_7$ (we'll discuss why when we get to yttrium). The generation of a brilliant red colour in fireworks and flares might not be enough to save strontium, and so we have our first candidate.

Group 13: B, Al, Ga, In, Tl. We'll come back to the transition metals and lanthanoids later, as we now skip across the *d* and *f* blocks to the *p* block. We've already mentioned the remarkable liquid properties of gallium above, so it's excluded. Aluminium is the most abundant metal in the Earth's crust, so that's gone as well. Indium is a nice example of an element that used to be boring (it had very few uses in the century following its discovery), but is now interesting owing to ITO (indium tin oxide), which is an indispensable part of every touchscreen device on the planet. Boron is a constituent of the world's strongest acid[5], which makes it totally interesting, while thallium has been used to poison many people over the years, especially, for some reason, in the 1950s in Sydney, Australia[6]. Nothing uninteresting in this group then.

Group 14: C, Si, Ge, Sn, Pb. The coordination chemist among us (A.G.B.) could make a cheap joke at carbon's expense here, but even he can't deny the fact that it's a pretty interesting element. Why does it alone, of all the elements, catenate to such an extraordinary degree? Depending on what history books you've read, lead may[7] or may not[8] have been responsible for the downfall of the Roman Empire, and that has to make it interesting. Staying with history, the almost certainly apocryphal story of Napoleon's tin buttons[9] (Napoleon invades Russia, winter sets in, the soldiers' tin buttons undergo a phase change at low temperature from the solid α form to the brittle β form, chaos ensues as soldiers are forced to fight one-handed while holding up their pants with the other) makes for a great lecture anecdote — and anything which keeps students awake must surely be interesting. Both silicon and germanium get a pass due to their extensive use, past and present, in our electronic age. So again, no boring candidates here.

Group 15: N, P, As, Sb, Bi. The importance of both nitrogen and phosphorus in living systems make them interesting, whereas, as with all poisons, arsenic is the elemental equivalent of terrible TV that we know we shouldn't watch, but for some reason can't

Was arsenic-poisoning responsible for the death of the famous racehorse Phar Lap? Credit: Zig Urbanski / Alamy Stock Photo

look away from. There are just so many good arsenic stories, especially the ones about the demises of both Napoleon[10] and Phar Lap[11] (Phar Lap was a highly successful New Zealand racehorse who, like many New Zealand things/people (Split Enz, John Clarke, the Pavlova, Fred Hollows) was claimed by Australia). And, perhaps somewhat ironically, it appears[12] to be an essential trace element for rats! Antimony is probably saved from being boring by the fact that pellets of the pure element were once used as a laxative and (this is the interesting bit) they were reusable and were actually passed (no pun intended) on from generation to generation[13]. Bismuth avoids the ignominy of being labelled boring by the relatively recent discovery[14] that ^{209}Bi is not the heaviest stable nucleus; it is in fact radioactive, with a half-life of a trifling 2.10×10^{19} years. In addition, crystals of the pure element are just gorgeous. Nothing uninteresting here.

Group 16: O, S, Se, Te, Po. Polonium achieved notoriety in 2006 when it was used in the assassination of Alexander Litvinenko. It was also the second element identified (but not isolated) by the Curies in that truckload of pitchblende (see radium above). Oxygen is interesting for many reasons, but the fact that it's pretty difficult to draw a Lewis structure for the O_2 molecule containing both a double bond and two unpaired electrons stands out — score 1 for molecular orbital theory! Sulfur is a component of a couple of amino acids and, by the same logic, selenium has to be interesting because it is part of 'the 21st amino acid', selenocysteine. That leaves tellurium, which looks like it might be a boring candidate. However, a couple of things save it. Firstly, half a microgram of TeO_2 taken by mouth will leave you with 'garlic breath' for 30 hours (15 mg can still be detected eight months later!)[13]. Secondly, radioactive ^{130}Te is the most abundant of the eight naturally occurring isotopes of Te (34%), while non-radioactive ^{128}Te is the second most abundant (32%). Think about that for a while. So, group 16 provides us with no boring candidates.

Group 17: F, Cl, Br, I, At. We've already mentioned the inherent interestingness of F, Br and At above. We each contain around 100 g of chlorine as the chloride ion, and we require about 70 µg of iodine daily, so neither of these elements can possibly be boring either. Short and sweet.

Group 18: He, Ne, Ar, Kr, Xe, Rn. As for group 17, we can quickly dispense with all of these elements because they are essentially unreactive which, as mentioned earlier, makes them somewhat fascinating. In fact, the compounds of group 18 elements that are known are incredibly interesting — witness the discovery[15] of Na_2He in 2017.

Group 3: Sc, Y, La(?), Ac(?). The fact that chemists haven't yet decided whether La and Ac should be members of group 3, or situated in the lanthanoids and actinoids, respectively, marks these elements as inherently interesting. Yttrium looks like it could certainly be boring, but is saved by its presence in $YBa_2Cu_3O_7$, the first high-temperature superconductor. Anything that nearly wins[16] a Nobel Prize surely has to be interesting. This leaves scandium. We are struggling to find anything interesting to say about scandium, except that its hydride was once thought to have the formula ScH_2, rather than ScH_3. Sounds potentially boring to us.

Group 4: Ti, Zr, Hf. Titanium is one of the ten most abundant elements in the Earth's crust, so that alone makes it pretty interesting. Not to mention that the right wrist of one of the authors (A.G.B.) is mostly titanium (don't ask). Hafnium and zirconium usually occur together, and are very difficult to separate. One might think that zirconium could be classed as interesting from an alphabetical point of view, being the last element when the elements are so ordered. It's also famous as a component of every cubic zirconia ring, so that probably saves it. Hafnium, on the other hand, we're having difficulty with. We'll save that until later.

Group 5: V, Nb, Ta. One of the few things that the older of us (A.G.B.) recalls from high school science lessons is that vanadium pentoxide, V_2O_5, is the catalyst used in sulfuric acid synthesis. Quite why he remembers that, he doesn't know, but it must have been interesting at the time. Vanadium steel was also used in the Model T Ford, which was quite a big deal in the early 1900s, so this element doesn't make the boring cut. We were just about to put niobium on the list of boring candidates, until we found out that it is used quite often in piercings — who knew? Tantalum finds extensive use in capacitors and was also used as the filament in the light bulbs on the Titanic. It's not boring.

Group 6: Cr, Mo, W. Chrome plating, stainless steel, a possible role in glucose metabolism (nobody is sure)[17], rubies, emeralds, sapphires and an Oscar™ for Julia Roberts (Erin Brockovich) make chromium pretty interesting. Molybdenum is the only one of the second-row transition metals to be an essential element, while everyone knows about tungsten lightbulb filaments (not to mention the fact that tungsten, amazingly, is found in some enzymes)[18]. So, no candidates from group 6 then.

Group 7: Mn, Tc, Re. Without manganese to aid in the conversion of water to oxygen at the water oxidation centre of Photosystem II, the world would be a very different place. Technetium doesn't occur naturally on the planet because all of its isotopes are radioactive and have long since decayed away, and it was also the first element to be prepared by humanity[19], which makes it really quite interesting. Rhenium was the last of the non-radioactive naturally-occurring elements to be discovered[20,21], and this alone has to make it interesting. We're halfway through the transition metals and it appears that they are nearly all non-boring.

Group 8: Fe, Ru, Os. Iron comprises 90% of all the metal refined on planet Earth. Enough said. Ruthenium was the first metal that could be induced[22] to bind to the notoriously unreactive N_2 molecule in the complex $[Ru(NH_3)_5N_2]^{2+}$, and was also instrumental[23] in Bob Grubbs' Nobel Prize

Vanadium steel was also used in the Model T Ford. Credit: Granger Historical Picture Archive / Alamy Stock Photo of 2005, so it has to be interesting. And osmium, for all its undoubtedly interesting chemistry, sticks in the mind as being the basis of what has to be the most bizarre terrorist attack plan ever. In 2004, media around the world reported a foiled bomb plot in London that was to use… osmium tetroxide. Apparently, this was going to blind and/or poison everyone in the vicinity of said bomb. Subsequently, this was proposed to be a hoax, but it is an interesting story[24].

Group 9: Co, Rh, Ir. Cobalt: well, there's Alfred Werner and the 1913 Nobel Prize. And the topic of almost too-many-to-count papers by one of us (A.G.B.)[25]. It's possibly the most interesting element on the periodic table — for one of us at least. The fact that elements which are involved in Nobel Prize victories are inherently interesting lets rhodium off the boring hook (William Knowles, 2001)[26], while iridium appears to have told us how and when the dinosaurs died off[27]. Three interesting metals there.

Group 10: Ni, Pd, Pt. Nickel-containing enzymes in microbes catalyse the conversion of carbon dioxide to acetate — that's pretty cool. And it's an essential element as well, so by definition, it's interesting. Where would organic chemists be without palladium? No more hydrogenations or easy C–C bond formation reactions (Nobel Prize 2010, Suzuki, Heck and Negishi)[28]. The discovery of cisplatin always makes for a great lecture anecdote and so platinum is interesting[29]. Not a boring element in sight in this group.

Group 11: Cu, Ag, Au. The simple fact that these three are collectively called 'the coinage metals' surely makes them interesting. Or, if we detail them individually, some molluscs use a copper compound to carry oxygen, silver has the highest electrical and thermal conductivity of all the metals, and gold is, well, gold — an indisputably beautiful element, the total of which that has been mined by humanity is estimated[30] to fit into a 20 m × 20 m × 20 m cube. Tell us that's not interesting!

Nuggets of element 79. Credit: Jim Lambert / Alamy Stock Photo

Group 12: Zn, Cd, Hg. Hmmm — there might be a boring candidate or two here — after all, these elements don't form compounds having the beautiful and varied colours that the 'real' transition metals do. But let's not be too hasty. Zn is an essential element, so that's out. Ni–Cd batteries, as the name suggests, do rather require the presence of Cd and we've already pointed out above that mercury is a liquid metal at room temperature and pressure. Nothing in Group 12, then.

The lanthanoids: La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu. Surely there must be several boring candidates in this shadowy and rarely-visited-unless-you're-interested-in-single-molecule-magnets part of the periodic table? So, let's dispense with the obvious interesting ones to begin with, and work our way down to the less-interesting ones.

We've already mentioned lanthanum, and the question of whether it's a lanthanoid or a transition metal. In fact, a similar argument could be made for lutetium ([Xe]$4f^{14}5d^{1}6s^{2}$), rendering this element somewhat interesting. Promethium is interesting for the same reason as technetium above, namely that it's all decayed away since the formation of the Earth, while both cerium and europium are saved from boring purgatory by the fact that they can actually access oxidation states other than +3. The latter is also interesting because Euro banknotes contain europium compounds as an anti-counterfeiting device[31] (we don't think the Americans or Japanese will be following suit here!). Dysprosium and gadolinium are both ferromagnetic metals at room temperature, while the much-touted neodymium magnets (actually an alloy with boron and iron) appear to be the strongest permanent magnets known.

Samarium (the first element to be named after a real person — albeit indirectly — as opposed to a God), also finds use in SmCo magnets, which have better corrosion resistance and work at higher temperatures than neodymium magnets. Sm(II) compounds have also found quite substantial use in organic chemistry[32]. Terbium is saved from ignominy by the fact that it is a component of Terfenol-D, a magnetostrictive material[33] that changes shape in the presence of a magnetic field — cool! Holmium has the greatest magnetic moment of all elements and is used in surgical Ho:YAG lasers. Erbium helps in the amplification signals in optical fibres, while ytterbium is one of the quartet of elements (Y, Er, Tb, Yb) named after the Swedish village of Ytterby. Science Writer John Emsley once said[13] of thulium 'there is nothing unique that draws one's attention to thulium'. Harsh. Many years ago, one of us (A.G.B.) attended a talk by Peter Atkins in which he certainly implied the same of praseodymium. So, these two elements deserve serious consideration for the title of most boring.

The actinoids: Th, Pa, U. We said at the start that we would neglect all elements after uranium, so we could easily have overlooked the above three elements. We've already said that uranium is interesting, but what about its two actinoid mates? Thorium was, for many years, used in gas lantern mantles, despite its radioactivity(!), while it also has the potential to be used as a cleaner nuclear reactor fuel than either uranium or plutonium. Protactinium is... hmm... pretty dull. A definite candidate.

The six finalists

So, from 92 candidates, we've whittled them down to six: Sr, Sc, Hf, Tm, Pr, Pa. At this point, it's probably prudent to return to those SciFinder numbers in Fig. 1 — Sr (365,610), Sc (74,724), Hf (105,156), Tm (52,725), Pr (87,565) and Pa (4,501) — and look at them in more detail. Let's consider each of these elements in turn.

Strontium. On the basis of the numbers above, it appears we might have been a touch hasty with strontium. It has (astonishingly!) more mentions in the literature than both 'chlorine' and 'fluorine', so there must be something pretty interesting about it. Does its being the only element named after a place in the UK count? Thought not. Although strontium has been used in such things as cathode ray tube colour TVs, fake diamonds, toothpaste for sensitive teeth and glow-in-the-dark plastics and paints, its most remarkable use is in atomic clocks — in fact, strontium clocks are so accurate, they respond to the change in gravity when lifted 2 cm off the Earth's surface[34]. Mind. Blown. But possibly the most interesting feature of strontium (and this comes courtesy of Oliver Sacks' wonderful book *Uncle Tungsten*[35]) is that when a saturated solution of strontium bromate slowly crystallizes, tiny bursts of light are emitted — one day we might get around to trying this in the lab. So, strontium is off the hook.

Hafnium. This is the next most referenced element from this set — more popular even than 'bromine' (in addition to cobalt, A.G.B.'s PhD was all about brominations and that was extremely interesting), so again, where's the interest coming from? Hafnium is the first element on the periodic table to have a full *f* shell of electrons, and for which the lanthanide (surely to be soon renamed lanthanoid) contraction is hence manifested, but we doubt there have been too many papers written about that. Organometallic hafnium complexes do appear to be useful in catalysing alkene polymerizations — and both N_2 and C–H activation reactions — so that's got to be useful, and therefore somewhat interesting.

Praseodymium. The element with the longest name of the first 92 comes next, and yes, its number of references does put it down amongst the more obscure elements (note: the longest element name is rutherfordium — score 1 for New Zealand!). In combination with neodymium, it is used in welders' and glassblowers' glasses to protect from both visible and infrared radiation. This combination of lanthanoids has the wonderful name 'didymium' — try saying that ten times fast. In fact, didymium was listed as an element on Mendeleev's original periodic table[36], but was later shown to be a mixture of praseodymium and neodymium, so we could say that praseodymium is one of only two elements to have been taken off the periodic table and then put back on again, the argument in the 1990s over the naming of some transuranium elements notwithstanding[37]. Praseodymium is used in the cathodes of NiMH (nickel metal hydride) batteries and also in magnets used in wind turbines and hybrid cars. So, there's at least something about this element that could be classified as interesting — but only just.

Scandium. Hmm. This is a transition metal that really doesn't get mentioned for anything other than the fact that it's the first of the transition metals. Unlike the rest of the transition metals, it only exhibits a single oxidation state (+3) — there are, of course, exceptions to this generalization, namely complexes of Sc(II) and Sc(I), but not many[38,39]. However, we have managed to find out one interesting thing about scandium — if you alloy it with aluminium (0.5% Sc), it greatly increases the strength of the aluminium and increases its melting point by about 800 °C. Not exactly riveting, but there's more — disclosure time, according to A.G.B., there is no greater game on the face of this planet than cricket — in 1979, in an Ashes test at the WACA, Dennis Lillie came out to the middle sporting an aluminium bat, and from what can be gleaned on the internet, said bat may well have contained scandium, so its position amongst the non-boring elements is cemented. However, balancing that, scandium/aluminium alloys are used in handguns — hardly a point in scandium's favour. But, given that one of us is a coordination chemist, it's not very likely that one of the transition metals will be chosen as the most boring element. This means, therefore, that the most boring element is going to be either a lanthanoid or actinoid.

Thulium. Yes, the very same element that was described[40] by John Emsley as 'the least significant element there is'. Well, at the moment, he's got a 50% chance of being correct. Given the very small number of references to thulium in the literature (although more than osmium, which surprises us), it would have to be pretty boring. At least, that's what we thought until we did some more digging. It's commonly stated around the internet (even by a learned society, no less!)[41] that the Nobel Laureate T. W. Richards (1914) had to recrystallize thulium bromate 15,000 times in order to obtain a pure sample and hence determine the atomic weight of thulium. Well, you might think that's vaguely interesting, but it's even more interesting when we tell you it's incorrect — who would have thought, something on the internet incorrect!? It so happens it was one Charles James, of New Hampshire College, who was the person who did all these recrystallizations[42]. And if you read the paper (and we urge you to so do, given that it gives detailed descriptions of real bucket chemistry), you'll see he could only carry some of them out at a rate of one or two per day. Wow. One assumes that the funding agencies wouldn't be too thrilled over that rate of progress nowadays. We reckon that's pretty interesting and would make a nice lecture anecdote.

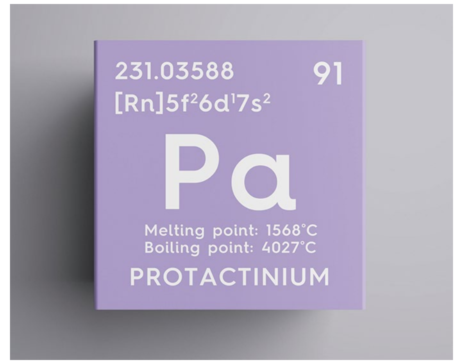
So that leaves just one.

Protactinium. SciFinder certainly doesn't rate it as being particularly popular. First isolated by Lise Meitner and Otto Hahn, it was called 'protoactinium' until 1949. The ^{233}Pa isotope is an intermediate in the production of fissile ^{233}U in thorium breeder reactors, and it is also formed from the decay of ^{241}Am in smoke detectors, so most of us have got some in our homes. Oh, and it's pretty rare. And that's about it, as far as we can find.

Conclusions

So, is protactinium the most boring element?

Well, not to someone who studies protactinium it's not. And the fact that there are 4,501 references to it on SciFinder confirms that there are people who have studied — and currently study — protactinium[43–46]. And this is the case for all of the elements on the periodic table; as you read this essay, every element is probably being studied by someone in a laboratory somewhere on the planet. As we said in the introduction, every element is unique — they have their own properties that are not replicated by any of the other 117, and therein lies the fact that there is no such thing as a boring element. Yes, some are undoubtedly more popular than others, but that doesn't make the others inherently less interesting. Sadly, in our experience, many chemists think that their own small area of speciality is the most important thing on the planet, and do somewhat tend to disparage areas of chemistry that lie outside their very narrow field of interest — be honest, you've all done it. We know we have. But as chemists, in this sesquicentennial year of the periodic table, we should be revelling in the astonishing diversity of all the elements — there's not a boring one amongst them. ❐



Protactinium — not quite the most boring element. Credit: Alexander Nedviga / Alamy Stock Photo

Rebecca E. Jelley[1] and Allan G. Blackman[2]*
[1]School of Chemical Sciences, University of Auckland, Auckland, New Zealand. [2]Department of Chemistry, School of Science, Auckland University of Technology, Auckland, New Zealand.
**e-mail: allan.blackman@aut.ac.nz*

Published online: 29 July 2019
https://doi.org/10.1038/s41557-019-0307-9

References

1. Blackman, A. & Ballance, A. Elemental. *Radio New Zealand* https://www.rnz.co.nz/programmes/elemental (2019).
2. Boring, adj. 2. *OED Online* (Oxford University Press, accessed 10 June 2019); https://www.oed.com/view/Entry/21667
3. The Nobel Prize in Physics. *The Nobel Prize* https://www.nobelprize.org/prizes/physics/1997/summary/ (2019).
4. Mould, R. F. *Brit. J. Radiol.* **71**, 1229–1254 (1998).
5. Cummings, S., Hratchian, H. P. & Reed, C. A. *Angew. Chem. Int. Ed.* **55**, 1382–1386 (2016).
6. Donnelly, M. Post-war days of thallium and old lace. *The Daily Telegraph* (22 May 2011).

7. Woolley, D. E. *Neurotoxicology* **5**, 353–361 (1984).
8. Dutrizac, J. E., O'Reilly, J. B. & MacDonald, R. J. C. *CIM Bull.* **75**, 111–115 (1982).
9. Samet, C. & Higgins, P. J. *J. Chem. Educ.* **82**, 1496–1500 (2005).
10. Lugli, A. et al. *Adv. Anat. Pathol.* **18**, 152–158 (2011).
11. Kempson, I. M. & Henry, D. A. *Angew. Chem. Int. Ed.* **49**, 4237–4240 (2010).
12. Uthus, E. O. *J. Trace Elem. Exp. Med.* **16**, 345–355 (2003).
13. Emsley, J. *Nature's Building Blocks: An A-Z Guide to the Elements* (Oxford University Press, 2011).
14. Beeman, J. W. et al. *Phys. Rev. Lett.* **108**, 062501 (2012).
15. Dong, X. et al. *Nat. Chem.* **9**, 440–445 (2017).
16. The Nobel Prize in Physics. *The Nobel Prize* https://www.nobelprize.org/prizes/physics/1987/summary/ (2019).
17. Vincent, J. B. *Met. Ions Life Sci.* **13**, 171–198 (2013).
18. Moura, J. J. G., Bernhardt, P. V., Maia, L. B. & Gonzalez, P. J. *J. Biol. Inorg. Chem.* **20**, 181–182 (2015).
19. Perrier, C. & Segre, E. *J. Chem. Phys.* **5**, 712–716 (1937).
20. Noddack, W. & Tacke, I. *Naturwissenschaften* **13**, 567–571 (1925).
21. Berg, O. & Tacke, I. *Naturwissenschaften* **13**, 571–574 (1925).
22. Allen, A. D. & Senoff, C. V. *Chem. Commun*. 621–622 (1965).
23. The Nobel Prize in Chemistry. The Nobel Prize https://www.nobelprize.org/prizes/chemistry/2005/summary/ (2019).
24. Bhattacharya, S. Experts divided over poison bomb claim. *New Scientist* (April 7 2004).
25. Blackman, A. G. in *Encyclopedia of Inorganic Chemistry* 1st edn (eds King, R. B., Crabtree, R. H., Lukehart, C. M., Atwood, D. A. & Scott, R. A.) 967–991 (Wiley, 2006).
26. The Nobel Prize in Chemistry. *The Nobel Prize* https://www.nobelprize.org/prizes/chemistry/2001/summary/ (2019).
27. DePalma, R. A. et al. *Proc. Natl Acad. Sci. USA* **116**, 8190–8199 (2019).
28. The Nobel Prize in Chemistry. *The Nobel Prize* https://www.nobelprize.org/prizes/chemistry/2010/summary/ (2019).
29. Lewis, R. From Basic Research to Cancer Drug: The Story of Cisplatin. *The Scientist Magazine* (July 5 1999).
30. Prior, Ed. How Much Gold is there in the World. *BBC News Magazine* (April 1 2013).
31. Bünzli, J.-C. *Nat. Chem.* **2**, 696 (2010).
32. Concellon, J. M., Rodriguez-Solla, H., Concellon, C. & del Amo, V. *Chem. Soc. Rev.* **39**, 4103–4113 (2010).
33. Parpia, D. Y., Tanner, B. K. & Lord, D. G. *Nature* **303**, 684–5 (1983).
34. Getting better all the time: JILA strontium atomic clock sets new records. *EurekAlert!* (April 21 2015).
35. Sacks, O. *Uncle Tungsten* (Penguin Random House, 2002)
36. Mendelejeff, D. *Zeitschrift fuer Chemie* **12**, 405–406 (1869).
37. Stokstad, E. *Science* **275**, 1570 (1997).
38. Woen, D. H. et al. *Angew. Chem. Int. Ed.* **56**, 2050–2053 (2017).
39. Arnold, P. L., Cloke, F. G. N., Hitchcock, P. B. & Nixon, J. F. *J. Am. Chem. Soc.* **118**, 7630–7631 (1996).
40. Gray, T. *The Elements: A Visual Exploration of Every Known Atom in the Universe* (Black Dog & Leventhal Publishers, 2012).
41. *The Periodic Table: Thulium* (Royal Society of Chemistry, 2019); http://www.rsc.org/periodic-table/element/69/thulium
42. James, C. *J. Am. Chem. Soc.* **33**, 1332–1344 (1911).
43. Deubner, H. L. et al. *Chem. Eur. J.* **25**, 6402–6411 (2019).
44. Naubereit, P. et al. *Phys. Rev. A* **98**, 022506 (2018).
45. Naubereit, P., Gottwald, T., Studer, D. & Wendt, K. *Phys. Rev. A* **98**, 022505 (2018).
46. Varga, Z., Nicholl, A., Hrnecek, E., Wallenius, M. & Mayer, K. *J. Radioanal. Nucl. Chem.* **318**, 1565–1571 (2018).

Acknowledgements

Many thanks to Alison Ballance and the team at RNZ for turning the Elemental podcast (mentioned at the start of this article) into reality.

Author contributions

The manuscript was jointly prepared by R.E.J. and A.G.B.

Competing interests

The authors declare no competing interests.