

Electron configurations and the group 3 question

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Abstract

Twelve arguments based on or associated with electron configurations of the d or f block elements, absent of any other considerations, support (a) cerium-thorium and lutetium-lawrencium as the first and last dyads of the f-block; and hence (b) Group 3 as Sc-Y-La-Ac, on regularity grounds. The least common form of periodic table with Group 3 as Sc-Y-Lu-Lr does not accommodate the impact of the delayed appearance of the first f electron.

Keywords electron configurations, Group 3, actinides, lanthanides, periodic table

Background

A recent provisional report from the IUPAC project tasked with making recommendations about the constitution of group 3 of the periodic table suggested that “perhaps” the group “could” be composed of Sc-Y-Lu-Lr in order to avoid splitting the d-block into two portions (Scerri 2021).¹ Such a split occurs in the rarely seen 32-column form of periodic table when group 3 is composed of Sc-Y-La-Ac (Fig. 1).

H																														
Li	Be																													
Na	Mg																													
K	Ca	Sc																											Ti	--
Rb	Sr	Y																											Zr	--
Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf														--
Fr	Ra	Ac	Th	Pa	U	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf														--

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Li	Be																													
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Rb	Sr																											Y	Zr	--
Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf														--
Fr	Ra	Ac	Th	Pa	U	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf														--

Figure 1. The two possible locations of group 3 in a 32-column periodic table. If the group is composed of Sc-Y-La-Ac the d-block is split into two portions.

¹ On the other hand, in a lecture given at the University of New Hampshire, Scerri said of the project, “we suggested...it *should* [italics added] be...Lu and Lr in group 3 rather than La and Ac.” (Scerri 2022, 53:05).

The project raised concerns about a split d-block on the grounds of this being highly uneven (having a 1:9 ratio). Elsewhere, Scerri and Parsons (2018, p. 146) observed that such a split occurs nowhere else in the periodic table. In fact, a more uneven split (1:13 ratio) occurs in the s block due to helium being placed over neon rather than beryllium. Scerri later refers to the split in the s block as representing [only] a 50:50 split of helium from hydrogen (2021, p. 401) as if underplaying its significance.

Given the arrangement of the modern periodic table is largely informed by a certain regularity in the electron configurations of its elements (Rayner-Canham 2021, pp. 72–73; Jensen 2015, p. 25, Petrucci et al. 2007, p. A-71) it seems incumbent to note that the form of table suggested by the IUPAC project subsequently introduces several irregularities in the arrangement of electron configurations due to not accounting for the delayed appearance of the first f electron. Thus, “In a chemical sense, the internal periodicity is displaced one element to the right.” (Imyanitov 2022, p.191)

Historically, so much importance was placed on regularity in electron configurations that the p elements B and Al, which were originally located over the d elements Sc-Y-La,² came to be moved over the p elements Ga, In, and Tl, in group 13, even though the periodic trends going down B-Al-Sc-Y-La were smoother than those going down B-Al-Ga-In-Tl (Parkes & Mellor 1943, p. 677; Greenwood & Earnshaw 2002, p. 223). As Parkes and Mellor wrote:

“The exact sub-classification to be adopted in...group [III] has in the past occasioned some difficulty, but it is now generally agreed that B and Al are best associated with Ga, In and Tl. This is supported by the conclusions at present accepted for the electronic configurations of these elements.”

The move occurred from the 1930's onwards, with the rise of modern electron theory, and appears to have taken until the 1960's to be effectively realized.³

It is somewhat ironic that the report of the IUPAC project concludes with an emphasis on presenting a periodic table to the “widest possible audience of chemists, chemical educators and chemistry students” apparently overlooking the fact that their suggested form of group 3 as Sc-Y-Lu-Lr introduces further chemistry-based irregularities (Vernon 2021).

At time of writing, IUPAC has not taken any further action with respect to the provisional report of the Group 3 project, at least until a new element is discovered. Given the report was only provisional and called for “feedback or suggestions from members of IUPAC and other readers” this is understandable. It may also be that IUPAC wish to avoid a Pluto-like-demotion situation in which a favourite form of periodic table is effectively deprecated (Scerri 2022, 54:23–54:41).

More broadly, IUPAC has never taken a position with regard to a recommended form of periodic table and it seems better to leave the question to the applicable context at the time. Of course, “students will always be annoyed when the answer is not ‘yes’ or ‘no’ but ‘on the one hand’...However there is value in learning that is how things are in real life” (Öhrström 2021), or being able to walk and chew gum at the same time: “There is room for both approaches.” (Imyanitov 2022, p.191)

² The first person to do so may have been Rang (1893, p. 178)

³ It may have taken this long for the teachings of the old chemists to be regarded as passé. Even then there were some holdovers. Pauling (1988, p. 182) has group 3 as B-Al-Sc-Y-La in his periodic table showing electronegativity values. Elsewhere he refers to the congeners of B as being Al-Sc-Y-La (p. 635).

Historical context

Jensen, in his 1982 *J. Chem. Educ.* article on the composition of group 3, suggested the ideal electron configuration for the f-block elements in general was $f^x s^2$ and that lanthanum, as $[\text{Xe}]4f^0 5d^1 6s^2$, would be considered an f-block element with an irregular configuration derived from its ideal configuration of $[\text{Xe}]4f^1 6s^2$. The last member of the 4f row would then be ytterbium with its configuration of $[\text{Xe}]4f^{14} 6s^2$, thereby completing the filling of the 4f row. The actinides would similarly start with actinium $[\text{Rn}]5f^0 6d^1 7s^2$.

Further analysis of Jensen's suggestion raises concerns to do with the irregularity of the start of the f block and blocks generally; dominant electron configurations; solid state electron configurations; and cation electron configurations.

The start of the f-block and blocks generally

1. Jensen's proposal to start the f block with lanthanum and actinium was objected to by Lavelle (2008) who noted it would represent the only instance where respective rows of a periodic table block started with elements having no relevant differentiating electrons.

2. In a Sc-Y-La-Ac table, the 4f row has one irregular start at Ce and the 5f row starts with four irregular elements.

In a Sc-Y-Lu-Lr table, the 4f row has two irregular starts with La and Ce and the 5f row starts with five irregular elements. The first element in the 6d row (Lr) is likewise irregular.

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

3. Further, in a periodic table with group 3 as Sc-Y-La-Ac, each periodic table block starts with, and is subtended by, the applicable differentiating electron: s at H; p at B; d at Sc; and f at Ce.

This is not the case in an Sc-Y-Lu-Lr table where the f-block starts with La although the first 4f electron does not appear until Ce, the following element.

Dominant electron configurations

4. In a periodic table with group 3 as Sc-Y-La-Ac the dominant or most common configuration in the d block is $d^{(n)} s^2$ with 21 occurrences; and in the f block is $f^{(n+1)}$ (where the +1 reflects the delayed start of filling of the 4f subshell) with 19 out of 28 occurrences, for a total of 40 dominant configurations.

If group 3 is instead composed of Sc-Y-Lu-Lr then the dominant or most common configuration in the d-block is $d^{(n)} s^2$ with 20 occurrences; and in the f block $f^{(n)} s^2$ with 19 out of 28 occurrences, for a total of 39 dominant configurations.

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

Solid state electron configurations

5. Since the lanthanides and actinides are solids in standard conditions of pressure temperature it is relevant to consider their electron configurations in this state in order to provide some more insight into their properties. For example, while gas phase neodymium is $[\text{Xe}]4f^4 6s^2$ it is $[\text{Xe}]4f^3 d^1 6s^2$ in the solid phase. In condensing to a solid, one 4f electron is transferred to the 5d subshell, which subsequently becomes a conduction electron, along with two 6s electrons (Johnson 1969, p. 1528).

Tables 1 and 2 compare the position numbers of the f block elements with the actual numbers of f electrons in their solid states, rather than gaseous states; there are 20½ matches in the first table compared to 6+ in the second, out of 28 elements.

4f row position	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Period 6	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actual number [^]	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	~7	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	~14	<u>14</u>
Period 7	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actual number [†]	<u>~1/2</u>	<u>~2</u>	<u>~3</u>	<u>~4</u>	<u>~5</u>	6	<u>7</u>	<u>8</u>	<u>9</u>	11	12	13	14	<u>14</u>

Table 1: Sc-Y-La-Ac periodic table f block showing solid state electron configurations (underlined, grey shading = match with position number)

5f row position	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Period 6	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Actual number [^]	>0?	1	2	3	4	5	<u>~7</u>	7	8	9	10	11	12	<u>~14</u>
Period 7	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
Actual number [†]	0	~1/2	~2	~3	~4	~5	6	7	8	9	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>

Table 2: Sc-Y-Lu-Lr periodic table f block showing solid state electron configurations

[^] Johansson and Rosengren (1975, p. 1367); Greenwood and Earnshaw (2002, pp. 1232, 1234): "...most of the metals are composed of a lattice of Ln^{III} ions with a 4fⁿ configuration and 3 electrons in the 5d/6s conduction band. Metallic Eu and Yb, however, are composed predominately of the larger Ln^{II} ions with a 4fⁿ⁺¹ configuration and only 2 electrons in the conduction band."

[†] Haire (2007, p. 65); Moore and van der Laan (2009, pp. 269; 270; 272; 275; 276; 283; 286); Lawson (2016, p. 87)

? The 4f levels in La, "lie just above the Fermi energy and could easily be occupied at least to a small extent" (Gschneidner 1993, p. 2) That said, such involvement would not be representative of the chemistry of La.

~ Some or all f electrons in the early actinides are itinerant, and become hybridized with ds electrons and orbitals. That, and the radioactivity and relative scarcity of the metals involved, makes it hard to pin down their f electron numbers beyond approximations, as denoted by a tilde. In thorium, the number of f electrons is shown as a fraction due to a 5f/6d overlap (Johansson et al. 1995, p. 282).

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

Cation configurations

6. Stewart (2018, p. 117) observed that an argument for lutetium in Group 3 was that the pth element in the f-block series, with the exception of [Ce and] Gd, has p (for place) f-electrons.

In contrast, Wulfsberg (2006, p. 3) emphasized the greater importance of the electron configurations of ions of the elements:

"...valence electron configurations of atoms and ions are also important in predicting the periodicity of chemical properties. Since ions are more important than isolated gaseous atoms for nearly all atoms, and important ions have no anomalous electron configurations, there is little reason to worry students with anomalous electron configurations of atoms: we prefer to teach 'characteristic' electron configurations without anomalies in the occupancies of d- and s-orbitals in the transition elements or d-, s-, and f- orbitals in the inner transition elements."

Thus, with lanthanum in Group 3, the number of f-electrons in the trivalent cations of the f-block elements correspond perfectly with their position in that block.

A similar observation applies to the divalent cations of the d-block elements. The number of d electrons in these ions corresponds to their position in the block. Trivalent cation configurations cannot be relied on here since there are no such species for the group 12 elements zinc, cadmium and mercury.

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

Survey of textbooks

A survey of 193 textbooks undertaken by the IUPAC Group 3 project (Wong & Scerri 2019) found that the Sc-Y-La-Ac form of table had steadily declined in popularity since the 90's but maintained a plurality; the IUPAC style of periodic table in which the f block was 15 elements wide had steadily increased in popularity since the 80's; and the Sc-Y-Lu-Lr form of table showed a decline in popularity from the 00's to the 10's (Fig. 2).

Given 32-column tables appeared only eight times in the survey, representing an occurrence rate of 4%, the basis for the IUPAC project's emphasis on avoiding a split d-block is not apparent.

Reger, Scott and Ball (2010, p. 295) wrote that "perhaps" the correct shape of the 32-column periodic table should feature a split d block given the electron configurations of La and Ac, but that "we avoid these structures by splitting the f block from the rest of the periodic table." (They show La below Y in the rest of their book.)

Earlier arguments

Five other properties related to electron configurations have been previously examined and shown to support the Sc-Y-La-Ac periodic table as the more regular form (Vernon 2021, pp. 159, 170, 176–177). A brief recap of these arguments, and a related newly arising argument, follows.

7. Incumbency. Lanthanum has the advantage of incumbency in the d-block, since the $5d^1$ electron appears for the first time in its structure whereas it appears for the third time in lutetium, having already made a brief appearance in gadolinium.

8. Predominant differentiating electrons. A 32-column table with an intact d-block is quantitatively less homogenous than a split d-block table. By this I mean a periodic table with Sc-Y-Lu-Lr, and helium over neon, has 13 differentiating electron discrepancies whereas a table with So-Y-La-Ac, and helium over neon, has 12.⁴

9. The f-block filling sequence. Placing lutetium and lawrencium under yttrium obscures the start of the filling of the f-block (it would appear to start at lanthanum) and visually truncates its double periodicity (it would be cut off at ytterbium whereas it would actually end in the d-block). Thus, the 4f subshell filling sequence, which runs from cerium to lutetium, is periodic, with two periods. After the occurrence of a half-full 4f subshell at europium and gadolinium, the filling sequence repeats with the occurrence of a full subshell at ytterbium and lutetium (Rokhlin 2003, pp. 4–5). A similar, but weaker periodicity (Wiberg 2001, pp. 1643–1645) is seen in the actinoids, with a half-full 5f subshell at americium and curium, and a full subshell at nobelium and lawrencium.

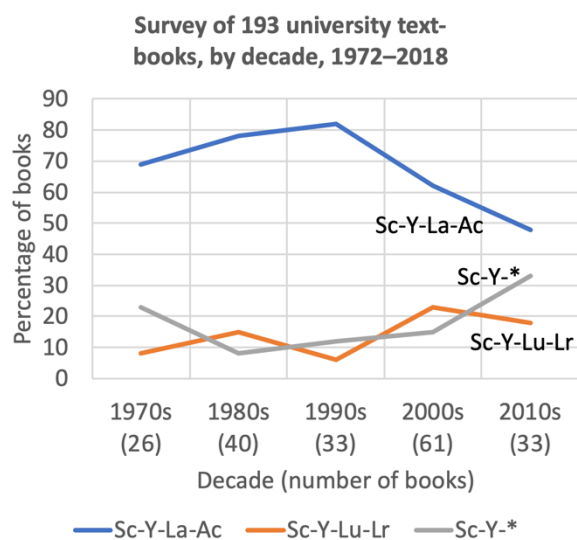


Figure 2: An IUPAC-commissioned survey of university textbooks on how group 3 of the periodic table is shown.

⁴ The differentiating electron is the electron that distinguishes an element from its predecessor. They are relevant from a chemistry perspective since they enable the periodic table to be parsed into four major blocks according to the predominant differentiating electron in each block, and each block shows distinctive physical and chemical properties (Stewart 2018a, p. 118).

10. The lanthanoid contraction. In a lanthanum table, the 4f-electron associated contraction naturally spans the f-block as cerium to lutetium (Housecroft & Sharpe 2008, p. 749). Cause and form are harmonized.

In a lutetium table the contraction does not start until the second element of the f-block; and the contraction then finishes after the end of the f-block, in the first period 6 d-block element, namely Lu. Cause and form are disaggregated. A table with lanthanum in Group 3 is thus more regular in this particular context.

11. The knock-on impact of the contraction on the 5d metals can shed further light on the Group 3 question. The result is that the 4d and 5d metals, in periods 5 and 6, tend to have similar radii. Figure 3 shows the differences in 12-coordination metallic radii⁵ between the period 5 and 6 elements for groups 1 to 14.

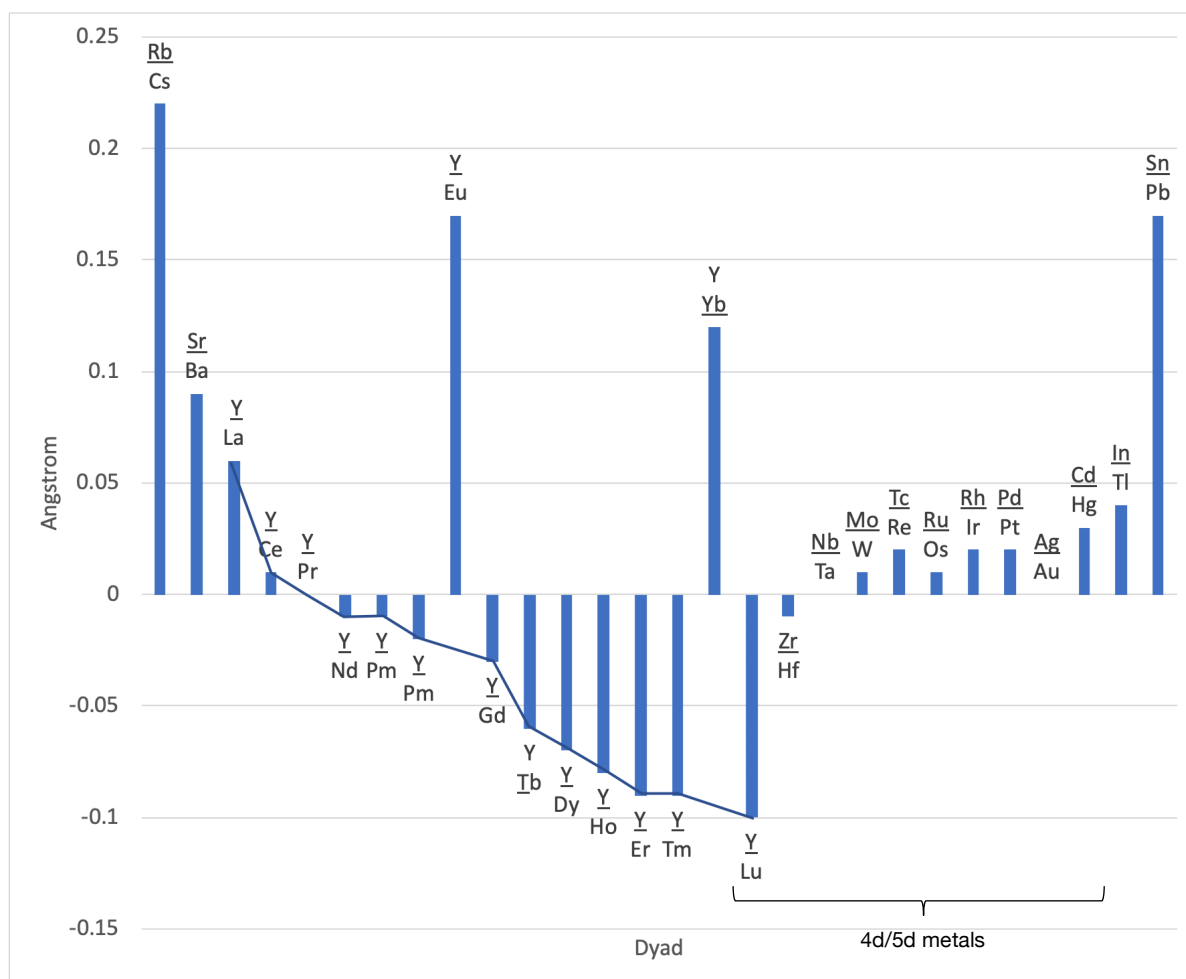


Figure 3: Differences in metallic radii of period 5 and 6 elements, for groups 1 to 14

The blue jagged line traces the progress of the Ln contraction among the Ln. It shows the difference in radii between Y and each of the metals from Ce to Lu. Thereafter, from group 4 (Zr/Hf) to about group 11 (Au/Ag) the radii are reasonably close.

⁵ Radii from Smith (1990, p. 117)

For group 3 with La, the trend along groups 1, 2 and 3 looks to be as expected⁶ whereas for Lu as a 5d metal in group 3, the difference in radii between it and Y appears anomalous compared to the rest of the 5d metals.

Figure 4 shows the differences in 6-coordination ionic radii⁷ between the period 5 and 6 elements for groups 1 to 14.

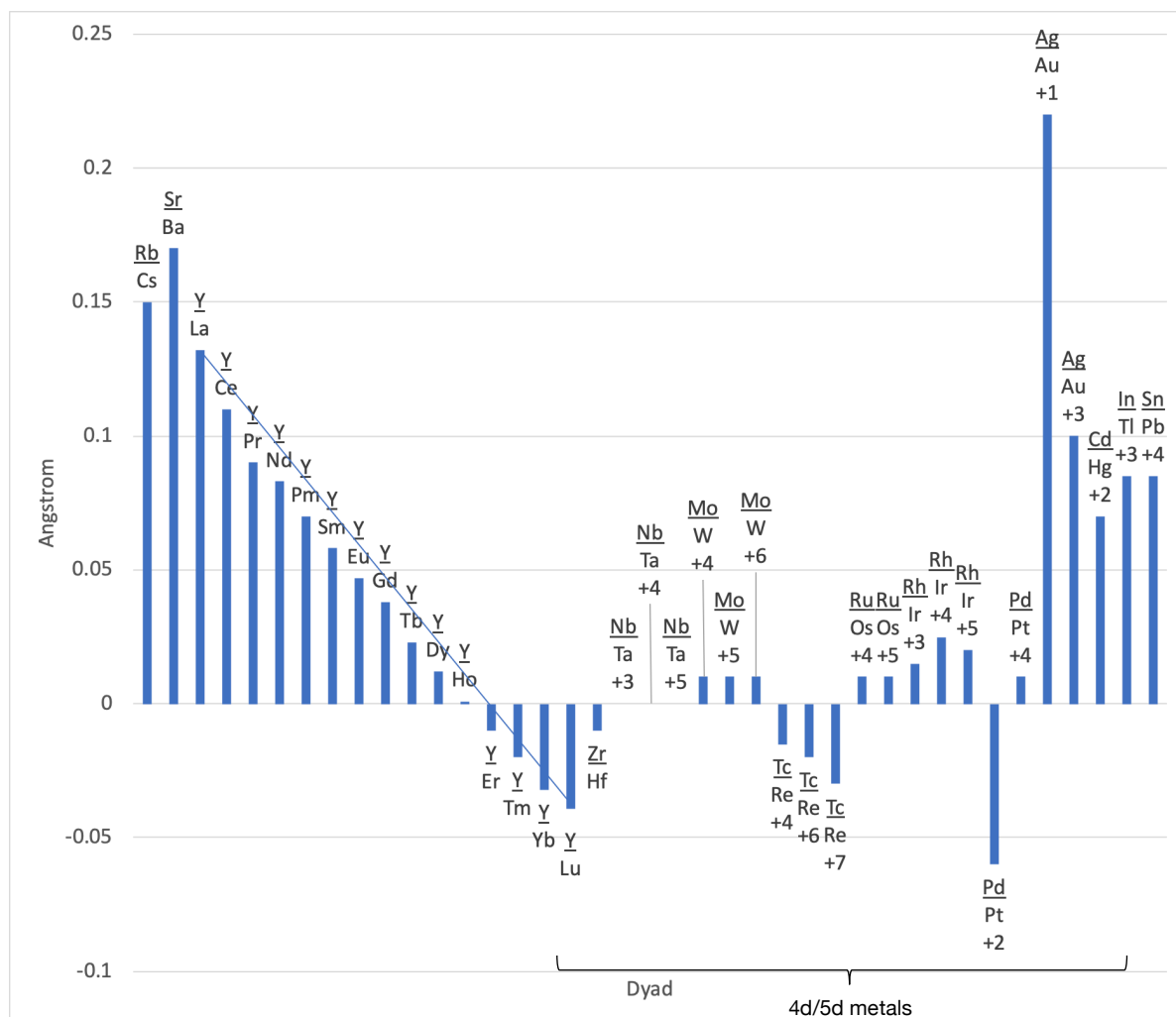


Figure 4: Differences in ionic radii of period 5 and 6 elements, for groups 1 to 14

There are more than 15 columns as the chart includes all the trivalent lanthanide cations and all the comparable differing oxidation states for the 4d and 5d ions.

The blue diagonal tracks the lanthanide contraction. It shows the difference in ionic radii between yttrium and each of the trivalent cations from cerium to lutetium. The knock-on effect of the contraction peters out after the platinum group metals.

The anomalies appear to be Y/Lu (if Lu is a 5d metal); maybe Tc/Re(+7); and certainly Pd/Pt(+2). The latter dyad was included by Shannon (1969, p. 944) in his list of ions exhibiting irregular coordination and which frequently resulted in inconsistent interatomic distances.

⁶ More broadly, Greenwood and Earnshaw (2002, p. 946) wrote that Sc-Y-La-Ac, “display the gradation of properties that might be expected for elements immediately following the strongly electropositive alkaline-earth metals and preceding the transition metals proper.”

⁷ Radii from Shannon (1976)

Yttrium has virtually the same ionic radius as Ho^{+3} and thus very similar chemistry (Leggett 2017, p. 434; Cotton 2018, p. 292) whereas if lutetium was a genuine 5d metal it would be expected to have an ionic radius closer to that of yttrium.

Based on metallic and ionic radii, the La form is more regular. Conversely, while the Lu form looks more regular, it introduces another irregularity elsewhere. Or one could turn things around and say that the La table is more irregular when seen in the rarely occurring 32-column form. But since this form is so rarely seen whereas the similarities between the 4d and 5d metals are an omnipresent phenomenon, effectively no one is particularly concerned about the 32-column form.

Further support for La under Y on the basis of atomic radii was alluded to by Atkins (2019, p. 6):

"The periodic table and the concept of the elements of education inspires all manner of other thoughts. One is the desert-island thought: if you were asked to identify the central elemental concept summarized by the periodic table...with you isolated on a conceptual desert island and asked to set about rationalizing chemistry, what would it be? My choice would be atomic radius. In molecular biology a common precept is that shape determines function, with shape interpreted as including size, I think that the same maxim applies in the less elaborate region of chemistry. Atomic radius correlates with ionization energy and electron affinity, and thus it correlates with much of the energetics of bond formation.

Atomic radius controls, perhaps even more than simple energetics, the numbers and arrangements of bonds that an element can form, and so is central to considerations of bonding and the formation and stereochemistry of compounds. Atomic radius plays a crucial role in the mechanisms of reactions, both in organic and inorganic chemistry, especially in the formation of intermediates and transition complexes. Atomic radius plays a role in the arrangement of electrons around nuclei, as well as that arrangement affecting the radius. When the elements form compounds, the sizes of the constituent atoms affect the size of the molecules and through that size (and the underlying aspects of the energetics of electron excitation, itself size-dependent) the intermolecular forces that determine the physical properties of the compounds. It is hard, in fact, to identify a property that cannot, with sufficiently deep probing, correlate in some way with atomic radius. Function, does indeed follow form and should perhaps be a fundamental element of education."

While the similarity of radii of the 4d and 5d metals is due to the knock-on impact of the Ln contraction the regularity of this trend turns out to depend, in part, on the composition of group 3.

It has been known for over half a century that metallic lutetium resembles closely metallic erbium and holmium (except that it melts at a slightly higher temperature and is essentially nonmagnetic) and that its metallurgy is almost identical to that of holmium (Spedding & Beaudry 1968, p. 378).

As far as the stoichiometry of binary compounds is concerned, yttrium was reported to be more like lanthanum than lutetium, with the latter appearing in a four-element cluster of erbium, holmium, lutetium and gadolinium, as observed by Restrepo (2018, pp. 94–95)

Based on the stability of 2,198 binary compound bonds occurring between 97 elements, lanthanum was found to cluster separately from the cerium to lutetium series (Liu et al. 2019).

Cotton et al. (2022), on the basis of a correlation of overall structural differences with the size of the metal ions, found, "no true chemical basis for arranging Lu rather than La in one triad with Sc and Y." Further, "We would say that Sc, Y, and La, show a progression of structural properties and that Lu does not fit into this progression as well as La does." (Cotton S 2023, pers. com., Feb 11).

12. The most important orbital in a chemical sense. While gas phase electron configurations appear to indicate that lanthanum $\text{Xe}5d^16s^2$ and lutetium $\text{Xe}4f^{14}5d^16s^2$ have equal claims to the position under yttrium, lanthanum is not subject to the lanthanoid contraction (as is the case with scandium and yttrium) whereas lutetium is, having incurred a 16.5% reduction in ionic radius.

Lutetium is subsequently the least basic of the lanthanoids.

On this basis, including that the most important sub-orbital is 4d for lanthanum and 4f for lutetium, and that the progressive filling of the 4f subshell contributes to the uniform and characteristic +3 oxidation state among the metals concerned (Mingos 1998, p. 375; Cotton 2006, p. 12), placing lanthanum under yttrium results in a more congruent chemical periodic table.

Electron configuration analogy

The total (i.e., core plus valence) electronic configurations of lanthanum and actinium are closer to those of scandium and yttrium than they are to the configurations of lutetium and lawrencium (due to their filled 4f subshells).

According to Jensen (1982 p. 635–636) this is a misleading argument since intra-period (Lu–Hg) and intragroup (Sc–Lu) electron configurations favour Lu under Y. That is to say all the period 6 d block elements would have a filled f shell and in going from period 5 to 6 there would be a consistent addition of 32 to the atomic number.

However, not only does the s-block already break this pattern (going from Sr to Ba does not add 4f electrons, but going from Te to Po does), but the symmetry in atomic number is already broken in period 1 for chemistry-based reasons: consider H and Li ($Z = 1, 3$) versus He and Ne ($Z = 2, 10$). Consistency in going from period 5 to period 6 (Lu–Hg) further introduces the irregularities that are the subject of this article.

While the differences between the chemistry of La and Lu are obviously not of the same order, it should at least raise the possibility that Jensen's argument needs to be assessed in light of other considerations such as the anomalous difference in radii between Y and Lu, as 4d and 5d metals, as explored in argument 12 of this paper.

Conclusion

The twelve numbered arguments discussed or mentioned in this paper, each related to electron configurations, show that Group 3 as Sc–Y–La–Ac provides a more regular periodic table. Thus, while the hood or bonnet of the car may be irregular, given the split d block that occurs in the rarely seen 32-column form, the engine runs smoothly. Conversely, a periodic table with Group 3 as Sc–Y–Lu–Lr, while having an aesthetically more pleasing appearance due to the lack of a split d block in the 32-column form, introduces multiple irregularities in the pattern of electron configurations or associated properties. The hood or bonnet of the car is streamlined but the engine runs irregularly.

References

- Atkins, P.: Elements of Education, Chemistry International **41**, 4, 4–7 (2019)
- Cotton, S.A.: Lanthanide and Actinide Chemistry. Wiley, Chichester (2006)
- Cotton, S.A.: The Rare Earths, a challenge to Mendeleev, no less today, in Giunta et al. (eds), 150 Years of the Periodic Table. Perspectives on the History of Chemistry, Springer, Cham (2018)
- Cotton et al. A comparison of the structural chemistry of scandium, yttrium, lanthanum and lutetium: A contribution to the group 3 debate, Coordination Chemistry Reviews, **455**, 214366 (2022)
- Greenwood, N.N., Earnshaw, A.: Chemistry of the Elements, 2nd edn., Butterworth-Heinemann, Oxford (2002)
- Gschneidner, K.A. Systematics and anomalies, Journal of Alloys and Compounds, **192**, 1–2, 1–10 (1993)
- Haire R.G.: Insights into the bonding and electronic nature of heavy element materials. Journal of Alloys and Compounds. **444–445**, 63–71 (2007)
- Imyanitov, N.S.: Periodic tables for cations +1,+2,+3 and anions –1. Quantitative characteristics for manifestations of internal periodicity and kinosymmetry. Found Chem **24**, 189–219 (2022).
- Jensen, W. B.: The positions of lanthanum (actinium) and lutetium (lawrencium) in the periodic table. J. Chem. Educ., **59**, 8, 634–636 (1982)
- Jensen, W.B.: The positions of lanthanum (actinium) and lutetium (lawrencium) in the periodic table: an update. Found Chem **17**, 23–31 (2015).
- Johansson, B. Abuja, R. Eriksson, O., Wills. J.M.: Anomalous fcc crystal structure of thorium metal, Physical Review Letters, **75**, 2, 280–283 (1995).
- Johansson, B., Rosengren, A.: Interpolation scheme for the cohesive energies for the lanthanides and actinides, Phys. Rev. B, **11**, 4, pp. 1367–1373 (1975)

- Johnson, D.A.: Third ionization potentials and sublimation energies of the lanthanides. *J. Chem. Soc. A*, 1525–1528 (1969)
- Lavelle, L.: Lanthanum (La) and actinium (Ac) should remain in the d-block. *J. Chem. Educ.*, **85**, 11, 1482 (2008)
- Lawson, A.C.: 5f-electron localisation in the actinide metals: Thorides, actinides and the Mott transition. *Philosophical Magazine Letters*, **96**, 3, 85–89 (2016)
- Leggett, R.: Biokinetics of yttrium and comparison with its geochemical twin holmium. *Journal of Radiological Protection*, **37**, 2, 434–449 (2017)
- Liu, R., Mao, G., Zhang, N.: Research of chemical elements and chemical bonds from the view of complex network. *Found. Chem.*, **21**, 193–206 (2019)
- Mingos, D.M.P.: *Essential Trends in Inorganic Chemistry*. Oxford University Press (1998)
- Moore, K.T., van der Laan, G.: Nature of the 5f states in actinide metals. *Reviews of Modern Physics*, **81**, 1, 235–298 (2009)
- Öhrström, L.: email to Eric Scerri. In Scerri (2022), 54:23.
- Parkes, G.D., Mellor, J.W.: *Modern Inorganic Chemistry*, impression of 1939 edition, Longmans, Green and Co., London (1943)
- Pauling, L. *General Chemistry*, Dover Publications, New York (1988)
- Petrucci, R.H. et al.: *General Chemistry: Principles and Modern Applications*, 9th ed., Pearson/Prentice Hall, Upper Saddle River, N.J
- Rang, P.J.F.: The Periodic arrangement of the elements, *Chemical News*, **67**, (1893)
- Rayner-Canham, G.R.: *The Periodic Table: Past, Present, and Future*, World Scientific, Singapore (2020).
- Reger, D.L., Goode, S.R., Ball, D.W.: *Chemistry Principles and Practice*, 3rd edn. Brooks/Cole Cengage Learning, Australia (2010)
- Restrepo, G.: The periodic system: A mathematical approach. In: Scerri, E., Restrepo, G. (eds.): *Mendeleev to Oganesson: A Multidisciplinary Perspective on the Periodic Table*. Oxford University Press, New York (2018)
- Rokhlin, L.L.: *Magnesium Alloys Containing Rare Earth Metals: Structure and Properties*. Taylor & Francis, London (2003)
- Scerri, E.R.: *The Periodic Table: Its Story and Its Significance*. Oxford University Press, Oxford (2021).
- Scerri, E.R.; Parsons, W.: What elements belong in Group 3 of the periodic table? In: Scerri, E., Restrepo, G. (eds.) *Mendeleev to Oganesson: A multidisciplinary perspective on the periodic table*, pp. 140–151. Oxford University Press, New York (2018).
- Scerri, E.R.: A brief history of the periodic table. Lecture given to the University of New Hampshire, March 1 (2022), https://www.youtube.com/watch?v=srqxDLY_RAE
- Shannon, R.D.: Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides, *Acta Cryst.* **A32**, 751–767 (1976).
- Shchukarev, S.A.: *Neorganicheskaya khimiya*, vol. 2. Vysshaya Shkola, Moscow (in Russian) (1974)
- Smith, D.W.: *Inorganic substances: a prelude to the study of descriptive inorganic chemistry*, Cambridge University Press, Cambridge (1990)
- Spedding F.H., Beaudry B.J.: Lutetium, in Hampel, C.A., *The Encyclopedia of the Chemical Elements*, Reinhold Book Corporation, New York
- Stewart, P.J.: Amateurs and professionals in chemistry. In: Scerri, E., Restrepo, G. (eds.) *Mendeleev to Oganesson: A Multidisciplinary Perspective on the Periodic Table*, pp. 66–79. Oxford University Press, New York (2018)
- Vernon, R.E.: The location and composition of Group 3 of the periodic table. *Found. Chem.* **23**, 155–197 (2021).
- Wells A.F.: *Structural Inorganic Chemistry*, 5th edn, Clarendon Press, Oxford
- Wiberg, N.: *Inorganic Chemistry*. Academic Press, San Diego (2001)
- Wong, J., Scerri, E.R.: Textbook survey of Group 3 depictions, progress tab, Dec (2019), <https://iupac.org/project/2015-039-2-200/>
- Wulfsberg, G.P.: Periodic table: Trends in the properties of the elements. In: *Encyclopedia of Inorganic Chemistry*, 2nd ed. John Wiley & Sons, New York (2006)

Acknowledgements

I thank:

- Bill Jensen for his work in seeking to clarify the composition of Group 3;
- Gavin Jared Bala, John Marks, Eugen Schwarz, Valery Tsimmerman, Mikhail Boldyrev, and Charles Meeker for helpful discussions;
- Simon Cotton and Paul Raithby for helpful discussions and for reviewing a draft of the article;
- Eric Scerri for pointing out to me, many years ago, apparent shortcomings in Jensen's 1982 article.