IUPAC Technical Report

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Discovery of the element with atomic number $Z = 118$ completing the 7[th] row of the periodic table (IUPAC Technical Report)

DOI 10.1515/pac-2015-0501
Received December 14, 2015; accepted December 29, 2015

Abstract: The fourth IUPAC/IUPAP Joint Working Party (JWP) on the priority of claims to the discovery of new elements 113, 115, 117 and 118 has reviewed the relevant literature pertaining to several claims. In accordance with the criteria for the discovery of elements previously established by the 1991 IUPAC/IUPAP Transfermium Working Group (TWG), and reinforced in subsequent IUPAC/IUPAP JWP discussions, it was determined that the Dubna-Livermore collaboration has fulfilled those criteria for element $Z = 118$. A synopsis of experiments and related efforts is presented.

Keywords: atomic number 118; discovery; eka-radon; IUPAC Inorganic Chemistry Division; IUPAP; new elements; periodic table; superheavy elements; transcopernicium; transfermium.

1 Introduction

The working party of independent experts drawn from IUPAC and IUPAP has addressed recent results of experiments searching for new heavy elements. Laboratories involved in the studies were contacted requesting papers relevant to the discoveries' consideration by the Joint Working Party on Discovery of Elements (JWP). The deadline for submission was 31 May 2012. Within the JWP, extensive review was conducted amongst members via electronic communications. This report is a continuation of the effort [1] that addressed elements 113, 115, and 117.

2 Criteria

The criteria that must be satisfied for the discovery of a new chemical element to be recognized were established by the IUPAP/IUPAC Transfermium Working Group (TWG) in 1991 [2]. Among those detailed criteria,

Article note: Sponsoring bodies: IUPAC Inorganic Chemistry Division; International Union of Pure and Applied Physics; see more details on page 159. The members of the IUPAC/IUPAP JWP are the authors of this report.

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sections particularly relevant to current deliberations follow. The numbers are the same as in the original work [2].

1. Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number Z not identified before, existing for at least 10^{-14} s. (The exact Z need not be determined, only that it is different from all Z-values observed before.)
2. The TWG realizes that the term 'reasonable doubt' is necessarily somewhat vague. Confirmation demands reproducibility. In the case of the new elements the TWG attaches considerable importance to reproducibility and would indeed like to be able to suggest that no new element should be recognized officially until the data upon which the claim is based have been reproduced, preferably in another laboratory and preferably by a different technique. However, it would appear unreasonable to apply such a demand of demonstrated reproducibility in all rigidity. We do not believe that recognition of the discovery of a new element should always be held up until the experiment or its equivalent have been repeated, desirable in principle as this may be. *However, we would waive this requirement only in cases where the data are of such a nature that no reasonable doubt is possible* (*for instance for data with a high degree of internal redundancy and of the highest quality*), *and under circumstances where a repetition of the experiment would imply an unreasonable burden*.
4. Most assignment properties do not alone allow sufficient certainty for assigning a unique value to Z; a combination of them may.
8. The TWG has a strong preference for publication in regular journals of international standing. However, it does not wish to take up a rigid position on this matter and would not wish to exclude from admissibility any form of *bona fide* publication of wide general accessibility.

These have served effectively as guiding principles since then by subsequent JWPs [1, 3–6].

In our considerations, positive factors include low background events, cross-bombardments, excitation functions, internal reproducibility in productions and in decays, physicochemical behavior, spatial correlations of evaporation residues and subsequent decays, and separators distinguishing Z-values. When such favorable properties occur in combination, the case may be regarded as greatly strengthened. Observation of characteristic K- and /or L-X-rays would obviously be beneficial but are currently still not an established part of the data used for assignment. Factors that are troublesome to the JWP, but not necessarily invalidating, include missing anchors to known/familiar nuclei, irreproducibility, unpersuasive chemistry, and high background situations.

We would like to point out that for the newest superheavy elements cross-bombardment experiments have achieved increasing importance. Cross-bombardments were established as one of the criteria for discovery in 1991 by the TWG [2] and their growing influence has been extensively deliberated by the JWPs. The key to this importance of cross-bombardment lies in the fact that even in the case of missing anchors the Z of the superheavy can be reliably assigned as the sum of the Zs of the target and projectile, if different combinations of projectile and target are found to produce the same states. Such combinations essentially circumvent possible misidentifications of Z.

3 Discovery profiles

The JWP report follows discovery profiles. The concise profile begins with the pertinent content from earlier reports [1, 3–5]. An historical account of the relevant publications is given appended with the JWP's consensus opinion(s) as to the value of the evidence on the basis of the criteria. Our resources for this report were articles submitted by 31 May 2012 by research groups and laboratories in response to formal solicitations by IUPAC. Additional relevant publications routinely available in research libraries or through modern electronic search techniques were also sought by the JWP.

Figure 1 is a convenient map of the superheavy nuclide region from the literature. The dashed N,Z grid coordinate at 184,114 indicates the composition of the hypothesized doubly magic stable nuclide ^{298}Fl.

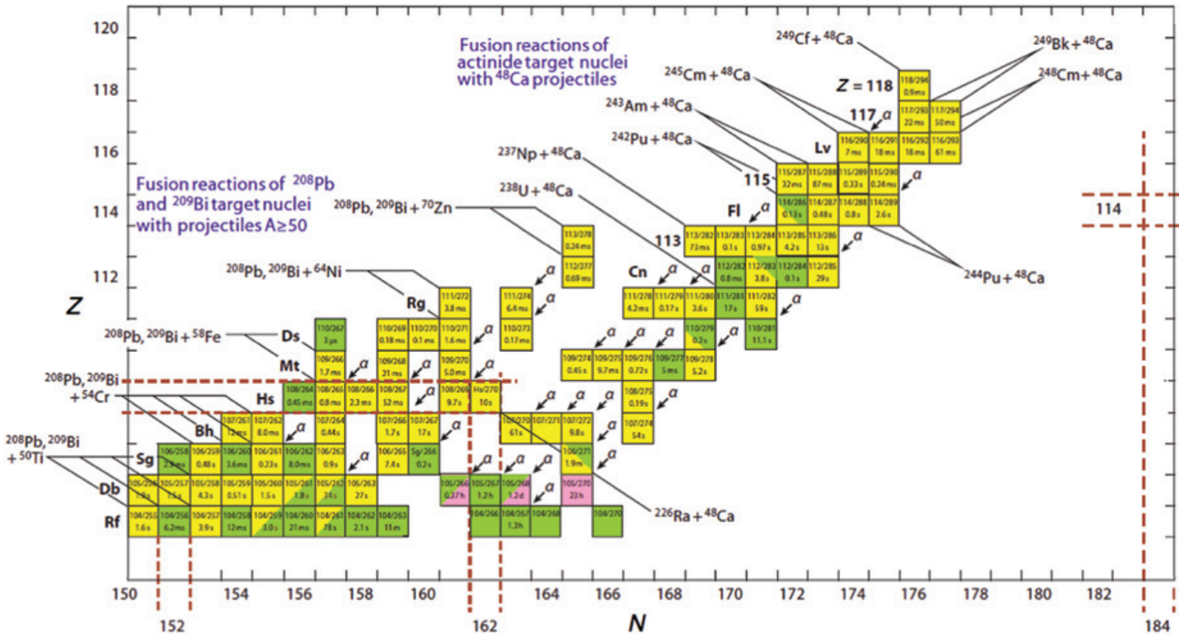

Fig. 1: Map of the region of superheavy nuclei relevant to this report including the reactions used to synthesize the various nuclides. (Adapted from [7].) The colors indicate different decay modes for nuclide *Z/A* along with its half life in milliseconds (ms), seconds (s), minutes (m) or hours (h) following the convention and data of [7], *q.v.*

3.1 Discovery profile for $Z = 118$

The 2006 collaboration of Oganessian *et al.* [8] observed three concordant events from the fusion of ^{48}Ca with ^{249}Cf reported to produce ^{294}118. The product underwent decay with average α-particle energy of 11.7 MeV in 1.3 ms to ^{290}Lv which, in all events, decayed with average α-energy 10.8 MeV in 14 ms to ^{286}Fl. Two chains of the latter isotope terminated by spontaneous fission, and the third event emitted a 10.16 MeV α-particle, all with an average lifetime of 0.23 s. The remaining event terminated by spontaneous fission of ^{282}Cn in 3 ms. The alpha-particle energies in MeV and the lifetime in milliseconds are tabulated below (Table 1) for each chain. One of these chains was reported by Oganessian *et al.* in 2002 [9].

PRIOR JWP ASSESSMENT: The three events reported for the $Z = 118$ isotope have very good internal redundancy but, with no anchor to known nuclei, do not satisfy the criteria for discovery.

A 2004 collaboration of Oganessian *et al.* [10] reported the observation of one complete alpha-decay chain assigned to the ^{290}Lv isotope produced by the ^{245}Cm(^{48}Ca, 3n) reaction. The ^{290}Lv alpha energy of 10.88 MeV is in moderate agreement with the 2002 measurement of this intermediate [8]. Another Oganessian *et al.* collaboration in 2004 [11] employed the ^{242}Pu(^{48}Ca, 3n) fusion to produce four chains with ^{286}Fl with an average alpha-particle energy of 10.21 MeV. The third ^{294}118 chain in [8] terminates with ^{286}Fl decay in agreement with that value.

Table 1: Properties (E_α/MeV and lifetime in milliseconds) of the alpha-decay chains commencing with ^{294}118 and terminating in spontaneous fission (SF).

Nuclide	Ref. [8] (2006)						Ref. [14] (2012)	
	E_α/MeV	Lifetime/ms	E_α/MeV	Lifetime/ms	E_α/MeV	Lifetime/ms	E_α/MeV	Lifetime/ms
^{294}118	11.65 ± 0.06	2.5	11.65 ± 0.10	0.5	11.8 ± 0.5	0.8	11.68 ± 0.06	0.14
^{290}Lv	10.71 ± 0.17	42	10.84 ± 0.10	1	10.80 ± 0.09	0.1	10.85 ± 0.07	29
^{286}Fl	SF	520	SF	11	10.16 ± 0.09	150	SF	3.5
^{282}Cn					SF	2.7		

In the previously cited 2006 Oganessian collaboration [8], an additional study, of the $^{245}Cm(^{48}Ca, 4n)$ fusion reaction, was used to produce nine chains following the path $^{290}Lv(\alpha) \rightarrow {}^{286}Fl(\alpha) \rightarrow {}^{282}Cn(SF)$ of which five were complete. The average α-particle energies were 10.90 MeV and 10.15 MeV, respectively, and are in excellent internal agreement and also concordant with the 2004 results.

A (LBNL) Lawrence-Berkeley collaboration of Stavstra *et al.* in 2009 [12] measured one alpha-decay chain from the fusion of ^{242}Pu with ^{48}Ca and observed ^{286}Fl produced by the 4n evaporation channel followed by spontaneous fission of ^{282}Cn. The ^{286}Fl observed α-particle energy of 10.23 MeV is in excellent agreement with the Oganessian collaborations above.

A newer collaboration of Ellison *et al.* at Berkeley in 2010 [13] also determined one alpha-decay chain from the fusion of ^{242}Pu with ^{48}Ca and observed ^{286}Fl produced by the 4n evaporation channel followed by spontaneous fission of ^{282}Cn. ^{286}Fl's α-particle energy of 10.31 MeV is in agreement with the earlier collaborations above.

In 2012, the Oganessian collaboration observed one 2 α-decay chain, starting with $^{294}118$ produced in the fusion of ^{48}Ca with ^{249}Cf followed by SF [14]. The α-particle energies match very well indeed with the decay chain seen in their previous (2006) collaboration as shown in the right column of the above Table 1. The original goal of the experiment was the study of $^{249}Bk + {}^{48}Ca$, but the 330 d half-life of ^{249}Bk resulted in up to 28 % of the target as ^{249}Cf. The new chain of $^{294}118$ was observed due to the target decay.

The case for discovery of $Z = 118$ is enhanced by the several cross bombardments independently producing descendants ^{290}Lv and ^{286}Fl as displayed in the diagram, Fig. 2, showing the results of fusion reactions of ^{48}Ca with ^{245}Cm or ^{242}Pu discussed above. The two experiments [8, 14] are consistent in their connection to known isotopes of Lv, Fl and Cn. This provides solid evidence that the new atomic number has been observed.

JWP ASSESSMENT: The 2006 Dubna–Livermore collaboration of Oganessian *et al.* produced three concordant decay chains commencing with $^{294}118$. This result was confirmed in 2012. Three other independent heavy element fusion studies served to identify and confirm the existence and decay properties of $^{294}118$ descendants ^{290}Lv and ^{286}Fl serving to link atomic numbers through cross bombardments. The Dubna–Livermore 2006 collaboration [8] has satisfied the criteria for discovery and its claim is now acknowledged as validated.

4 Comments

Identification of Z,N becomes more and more difficult in the pursuit of superheavy elements with heavy ion fusions. Development of direct physical methods to determine Z, particularly X-ray measurements as often envisaged, is of growing importance as is the desirability of employing exotic radioactive nuclear beams to access nuclides that are currently synthesized via the hot fusion route.

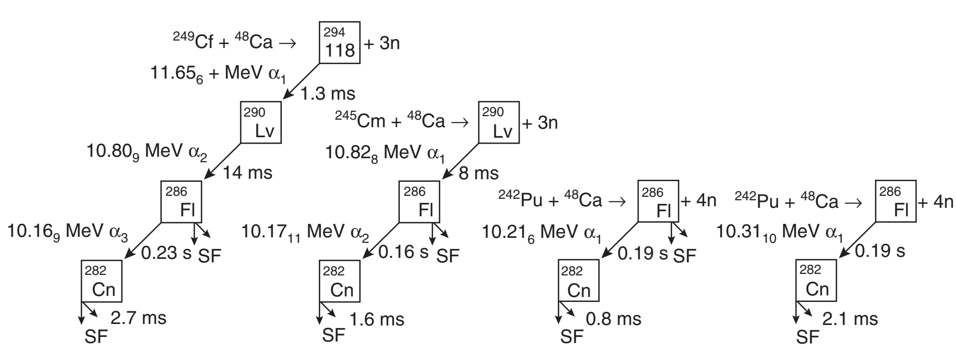

Fig. 2: Summary of the decay relevant work in the assignment of $Z = 118$. The cross bombardments for the confirmation of identification of $Z = 118$ daughters provide firm evidence that a new atomic number, distinct from previously observed atomic numbers, has been identified. Alpha particle energies in MeV and lifetimes in milliseconds (ms) or seconds (s) are shown.

5 Summary of JWP conclusions

The claim of the Dubna–Livermore 2006 collaboration for discovery of the element with atomic number $Z = 118$ is acknowledged as validated.

6 Membership of sponsoring IUPAC body

Membership of the Inorganic Chemistry Division Committee for the period 2012–2015 was as follows:

2012–2013: President: Loss, Robert D (Australia); Vice President: Reedijk, Jan (Netherlands); Secretary: Leskelä, Markku (Finland); Titular members: Mathur, Sanjay (Germany); Drabik, Milan (Slovakia); Sakai, Ken (Japan); Holden, Norman E. (USA); Öhrström, Lars R. (Sweden); Karen, Pavel (Norway); Tshuva, Edit Y. (Israel); Associate members: Ding, Tiping (China/Beijing); Garcia-Martinez, Javier (Spain); Buchweishaija, Joseph (Tanzania); Rabinovich, Daniel (USA); Vannier, Rose-Noelle (France); Kiliç, Adem (Turkey); National representatives: Abdul Aziz, Farina (Malaysia); Trendafilova, Natasha (Bulgaria); Prugovečki, Biserka (Croatia); Chandrasekhar, V. (India); Youngme, Sujittra (Thailand); Toma, Henrique (Brasil).

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This manuscript (PAC-REP-15-05-01) was prepared in the framework of IUPAC project 2012-047-1-200.

References

[1] P. J. Karol, R. C. Barber, B. M. Sherrill, E. Vardaci, T. Yamazaki. *Pure Appl. Chem.* **88**, 139–153 (2016).
[2] A. H. Wapstra. *Pure Appl. Chem.* **63**, 879 (1991).
[3] P. J. Karol, H. Nakahara, B. W. Petley, E. Vogt. *Pure Appl. Chem.* **73**, 959 (2001).
[4] P. J. Karol, H. Nakahara, B. W. Petley, E. Vogt. *Pure Appl. Chem.* **75**, 1601 (2003).
[5] R. C. Barber, H. W. Gäggeler, P. J. Karol, H. Nakahara, E. Vardaci, E. Vogt. *Pure Appl. Chem.* **81**, 1331 (2009).
[6] R. C. Barber, P. J. Karol, H. Nakahara, E. Vardaci, E. W. Vogt. *Pure Appl. Chem.* **83,** 1485 (2011).
[7] J. H. Hamilton, S. Hofmann, Y. T. Oganessian. *Annu. Rev. Nucl. Part. Sci.* **63,** 383 (2013).
[8] Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Lobanov, F. Sh. Abdullin, A. N. Polyakov, R. N. Sagaidak, I. V. Shirokovsky, Yu. S. Tsyganov, A. A. Voinov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, K. Subotic, V. I. Zagrebaev, G. K. Vostokin, M. G. Itkis, K. J. Moody, J. B. Patin, D. A. Shaughnessy, M. A. Stoyer, N. J. Stoyer, P. A. Wilk, J. M. Kenneally, J. H. Landrum, J. F. Wild, R. W. Lougheed. *Phys. Rev. C* **74**, 044602 (2006).
[9] Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Lobanov, F. Sh. Abdullin, A. N. Polyakov, I. V. Shirokovsky, Yu. S. Tsyganov, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, O. V. Ivanov, A. A. Voinov, K. Subotic, V. I. Zagrebaev, M. G. Itkis, K. J. Moody, J. F. Wild, M. A. Stoyer, N. J. Stoyer, C. A. Laue, D. A. Shaughnessy, J. B. Patin, R. W. Lougheed. *JINR Communication* D7-2002-287, Dubna (2002). [http://www.jinr.ru/publish/Preprints/2002/287(D7-2002-287)e.pdf]; *Lawrence Livermore National Laboratory Report*, UCRL-ID-151619 (2003).
[10] Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Lobanov, F. Sh. Abdullin, A. N. Polyakov, I. V. Shirokovsky, Yu. S. Tsyganov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, A. A. Voinov, G. V. Buklanov, K. Subotic, V. I. Zagrebaev, M. G. Itkis, J. B. Patin, K. J. Moody, J. F. Wild, M. A. Stoyer, N. J. Stoyer, D. A. Shaughnessy, J. M. Kenneally, R. W. Lougheed. *Phys. Rev. C* **69**, 054607 (2004).
[11] Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Lobanov, F. Sh. Abdullin, A. N. Polyakov, I. V. Shirokovsky, Yu. S. Tsyganov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, A. A. Voinov, G. V. Buklanov, K. Subotic, V. I. Zagrebaev, M. G. Itkis, J. B. Patin, K. J. Moody, J. F. Wild, M. A. Stoyer, N. J. Stoyer,

D. A. Shaughnessy, J. M. Kenneally, P. A. Wilk, R. W. Lougheed, R. I. Il'kaev, S. P. Vesnovskii. *Phys. Rev. C* **70,** 064609 (2004).
[12] L. Stavsetra, K. E. Gregorich, J. Dvorak, P. A. Ellison, I. Dragojević, M. A. Garcia, H. Nitsche. *Phys. Rev. Lett.* **103**, 132502 (2009).
[13] P. A. Ellison, K. E. Gregorich, J. S. Berryman, D. L. Bleuel, R. M. Clark, I. Dragojević, J. Dvorak, P. Fallon, C. Fineman-Sotomayor, J. M. Gates, O. R. Gothe, I. Y. Lee, W. D. Loveland, J. P. McLaughlin, S. Paschalis, M. Petri, J. Qian, L. Stavsetra, M. Wiedeking, H. Nitsche. *Phys. Rev. Lett.* **105**, 182701 (2010).
[14] Yu. Ts. Oganessian, F. Sh. Abdullin, C. Alexander, J. Binder, R. A. Boll, S. N. Dmitriev, J. Ezold, K. Felker, J. M. Gostic, R. K. Grzywacz, J. H. Hamilton, R. A. Henderson, M. G. Itkis, K. Miernik, D. Miller, K. J. Moody, A. N. Polyakov, A. V. Ramayya, J. B. Roberto, M. A. Ryabinin, K. P. Rykaczewski, R. N. Sagaidak, D. A. Shaughnessy, I. V. Shirokovsky, M. V. Shumeiko, M. A. Stoyer, N. J. Stoyer, V. G. Subbotin, A. M. Sukhov, Yu. S. Tsyganov, V. K. Utyonkov, A. A. Voinov, G. K. Vostokin. *Phys. Rev. Lett.* **109**, 162501 (2012).