**IUPAC Technical Report**

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# Discovery of the elements with atomic numbers $Z = 113$, 115 and 117 (IUPAC Technical Report)

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**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 RIKEN collaboration has fulfilled those Criteria for element $Z = 113$. The Dubna–Livermore–Oak Ridge collaborations claims for 115 and 117 are also in compliance. The discussion of element $Z = 118$ will appear in a subsequent report. A synopsis of experiments and related efforts is presented along with some commentary guiding future applications of the Criteria.

**Keywords:** atomic number 113; atomic number 115; atomic number 117; discovery; IUPAC Inorganic Chemistry Division; IUPAP; new elements; periodic table; super heavy 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. As usual, laboratories involved in the studies were requested to submit papers relevant to the discoveries for consideration by the Joint Working Party on Discovery of Elements (JWP). The deadline for submission was 31 May 2012. Within the JWP, an extensive review was conducted amongst members via electronic communications. The mandate of the working party was to review documentation, to make judgments on the priority claims, and to report to the two Unions. The JWP did not entertain post-deadline claims, published or otherwise, although more recent literature was consulted where relevance to the recommendations on submitted claims was clear. This report is not a comprehensive review and, for the most part, does not comment on studies unless directly germane to its deliberations.

**Article note:** Sponsoring bodies: IUPAC Inorganic Chemistry Division; International Union of Pure and Applied Physics; see more details on page 150. The members of the IUPAC/IUPAP JWP are the authors of this report. Discovery of the element with atomic number $Z = 118$ completing the 7th row of the periodic table (IUPAC Technical Report) is published in this issue, page 155.

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## 2 Criteria

Criteria that must be satisfied for the discovery of a new chemical element to be recognized were carefully and thoroughly defined by the IUPAP/IUPAC Transfermium Working Group (TWG) in 1991 [1]. As before, sections particularly relevant to balancing a sensibly conservative stance with the need for reasonable flexibility are paramount to our deliberations, always bearing in mind that an absolute proof of discovery is not required, while evidence beyond a reasonable doubt is. Flexibility has been guided by a waiver option italicized by us in the summary of relevant sections in the TWG Criteria that follows.

1. Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt of the existence of a nuclide with an atomic number $Z$ differing from previously known elements, 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.*
3. An experiment designed to demonstrate the existence of a new element must have two aspects. The first establishes physical and or chemical properties of samples suspected of containing (at least one atom of) the new element and that are sufficient to categorize it; these we call "characterization properties." The second extends to properties that are used to demonstrate that the characterization properties are indeed those of an unknown element; these we call "assignment properties." Some properties can be used for both purposes.
4. Most assignment properties do not alone allow sufficient certainty for assigning a unique value to $Z$; a combination of them may.
5. The assignment of $A$ can in principle influence the assignment of $Z$; priority cannot be denied if a wrong $A$-assignment does not influence the $Z$-assignment.
6. In the specific cases under consideration, nuclides of supposedly new elements have been obtained by bombarding targets of known composition with known particles, sometimes followed by chemical purification. Impurities in the targets are known to have caused confusion in some cases. In the region of the transfermium elements, however, their influence is now known and can be rather easily recognized, since impurities only matter if they produce SF (spontaneous fission) or high-energy $\alpha$-particle radioactivities.
7. 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 Criteria have served effectively as guiding principles by subsequent JWPs [2–5]. Those references should be consulted by interested parties as the Criteria serve to provide a uniform, consistent basis for definitive observation and interpretation that is generally agreed to by investigators. For efficiency in following, some of previous discussions are repeated in this report.

In the unlikely circumstance that a recommendation is shown by future investigations to be incorrect or to have overlooked alternatives, the priority of discovery can be nullified or modified as has been historically established.

In our considerations, positive factors include low background events, cross-reactions, 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 favorable properties occur in combination, the case may be regarded as greatly strengthened. Not all factors enter into consideration for each review. Observation of characteristic $K$- and /or $L$-X-rays would obviously be beneficial but are currently still not an established part of the measurement results. Factors that are troublesome to the JWP, but not necessarily invalidating, include missing anchors to known/familiar nuclei, rigidly demonstrated reproducibility, unpersuasive chemistry, and high background situations. Because of low production yields, excitation functions are becoming increasingly less quantitative and therefore less influential.

The assignment of $Z$ simply as the sum of the $Z$s of the target and projectile is a likely one provided the excitation energy of the compound system is low-enough to disfavor charged particle emission. In the case that the new nuclide can be connected to known atomic numbers by decay chains, the evidence is beyond a reasonable doubt. However, in the case where the decay chains end in non-specific fission decays, the current theoretical understanding of charged particle emission is insufficient, alone, to allow extrapolation to unknown $Z$ cases with the confidence necessary to satisfy Criteria and to establish priorities. In considering decay chains, the necessity that these be unbroken is vital. We would welcome further study of the matter to anchor new nuclides to known ones and to explore the exact conditions where charged-particle emission from super-heavy compound nuclei may compete with neutron emission. Confidence in $Z$-assignments is reinforced by the use of cross-reactions, particularly those that involve both even–even and even–odd mass or atomic number combinations.

We would like to point out that for the newest super heavy elements, cross-reaction experiments have achieved increasing importance. Cross-reactions were established as one of the Criteria for discovery in 1991 by the TWG [1] and their growing influence has been extensively deliberated within the previous and current JWPs. The key to this importance of cross-reaction lies in the fact that, even in the case of missing anchors, the $Z$ of the super heavy can be reliably assigned as the sum of the $Z$s 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 $Z$.

A somewhat ironic condition arises in the different characteristics of alpha-decay chains from even-even nuclides compared to odd-$Z$ nuclides. In the latter case, the reproducibility from experiment-to-experiment of alpha particle energies is seriously confounded by the many final states available for odd-even, even–odd and odd–odd systems, an effect not characteristic of even-even systems. But that same disadvantage in decay sequences can serve as a marker for misidentifying the $Z$ as being shifted due to proton loss at the initial step in the sequence of events as odd-$Z$ decay candidates can be distinguished from even-$Z$ cases.

## 3 Discovery profiles

The JWP report follows the previously used procedures for discovery profiles. Each concise profile begins with a reprise of the pertinent content from earlier reports [1–5] if any. An historical account of the relevant publications on each element 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. A listing appears at the end of this report.

The TWG chose "not to propose universal and rigid resolutions such as might lead to the assignment of absolute priorities but rather to support [the] concept of the discovery profile which … will lead to a more equitable appreciation of the range of contributions that might have been made. An absolute priority would often equate to an absolute injustice".

Below, in Figure 1, is a convenient map of the super heavy nuclide region from the literature [6]. The dashed $N$,$Z$ grid coordinate at 184,114 indicates the composition of the hypothesized doubly-magic nuclide $^{298}$Fl.

In the profiles, uncertainties associated with alpha-particle energies do not strictly follow a uniform construction procedure as the literature is not unvarying in its approach. Hence, those uncertainties are for guidance only.

## 3.1 $Z = 113$

A confounding feature of alpha decay in odd-$Z$ nuclei is the likely broad distributions of α-energies due to decays to excited daughter states. A good illustration can be found in those of $^{272}$Rg studied by Morita *et al.* [7]. The results indicate a distribution of α-energies as much as 0.8 MeV. The clustered transitions show nearly the same level lifetime suggesting that each cluster of α-decay transitions originates from a common parent state. This is consistent with the view that the different α-energies, negating reproducibility when few events are available, correspond to split daughter states of odd–odd or odd-$A$ nuclei.

The collaboration of Oganessian *et al.* [8] in 2004 studied the hot fusion reaction of $^{48}$Ca with $^{243}$Am and reported three chains beginning with $^{288}$115, continuing sequentially to $^{284}$113, $^{280}$Rg, $^{276}$Mt, $^{272}$Bh, were observed with good internal agreement and terminating with spontaneous fission of $^{268}$Db with mean lifetime of 23 h. At a different bombardment energy, one four member α-decay chain commencing at $^{287}$115, passing through $^{283}$113 and then $^{279}$Rg and $^{275}$Mt leading to $^{271}$Bh whose missing α-decay was inferred to lead to $^{267}$Db which decayed by spontaneous fission (with a 100 min lifetime). Data are summarized in the Table 1. None of the nuclides had been previously characterized.

The production of two chains of α-emitting nuclides was reported by Morita *et al.* from the cold fusion reaction of a bismuth-209 target with a $^{70}$Zn beam at the RIKEN heavy-ion facility in Japan, the first in 2004 [9] and the second in 2007 [10]. The former study reports the α-chain commencing with $^{278}$113 proceeding through $^{274}$Rg, $^{270}$Mt, $^{266}$Bh, and terminating via spontaneous fission decay assigned to $^{262}$Db. All α-energies and lifetimes were measured. In the subsequent study, a very similar sequence was found but with some reproducibility difficulties. The full α-energy for $^{270}$Mt was not measured; those for $^{266}$Bh were in disagreement (9.08 *vs.* 9.77 MeV); and the lifetimes for $^{262}$Db spontaneous fission were suggestively different (41 s *vs.* 0.8 s). For both chains, position-sensitive detectors were used as is the case in all investigations reviewed here. These provide a high degree of confidence that the observed decays are indeed sequential decays in each case. Nuclides reported in these chains do not correspond to established (recognized) isotopes (see the following figure). But a report of a single triple-coincidence of α-emitters commencing with the useful intermediate $^{266}$Bh had been

**Table 1:** Average decay properties of the chains originating with the $^{243}$Am($^{48}$Ca,3n)$^{288}$115 and $^{243}$Am($^{48}$Ca,4n)$^{287}$115 productions.

| Nuclide | Decay mode | $E_\alpha$/MeV | Half-life[a] |
|---|---|---|---|
| $^{243}$Am($^{48}$Ca,3n)$^{288}$115 | | | |
| $^{288}$115 | $\alpha_1$ | 10.46 ± 0.06 | 87 ms |
| $^{284}$113 | $\alpha_2$ | 10.00 ± 0.06 | 0.48 s |
| $^{280}$Rg | $\alpha_3$ | 9.75 ± 0.06 | 3.6 s |
| $^{276}$Mt | $\alpha_4$ | 9.71 ± 0.06 | 0.72 s |
| $^{272}$Bh | $\alpha_5$ | 9.02 ± 0.06 | 9.8 s |
| $^{268}$Db | SF/α/EC | | 16 h |
| $^{243}$Am($^{48}$Ca,4n)$^{287}$115 | | | |
| $^{287}$115 | $\alpha_1$ | 10.59 ± 0.09 | 32 ms |
| $^{283}$113 | $\alpha_2$ | 10.12 ± 0.09 | 100 ms |
| $^{279}$Rg | $\alpha_3$ | 10.37 ± 0.16 | 170 ms |
| $^{275}$Mt | $\alpha_4$ | 10.33 ± 0.09 | 9.7 ms |
| $^{271}$Bh | $\alpha_5$ (?) | Missing | Beam off |
| $^{267}$Db | SF | | 73 min |

[a]Either half-lives or lifetimes will be shown, depending on the original published data. Half-life = (0.693) × lifetime = ($\log_e$2) × lifetime.

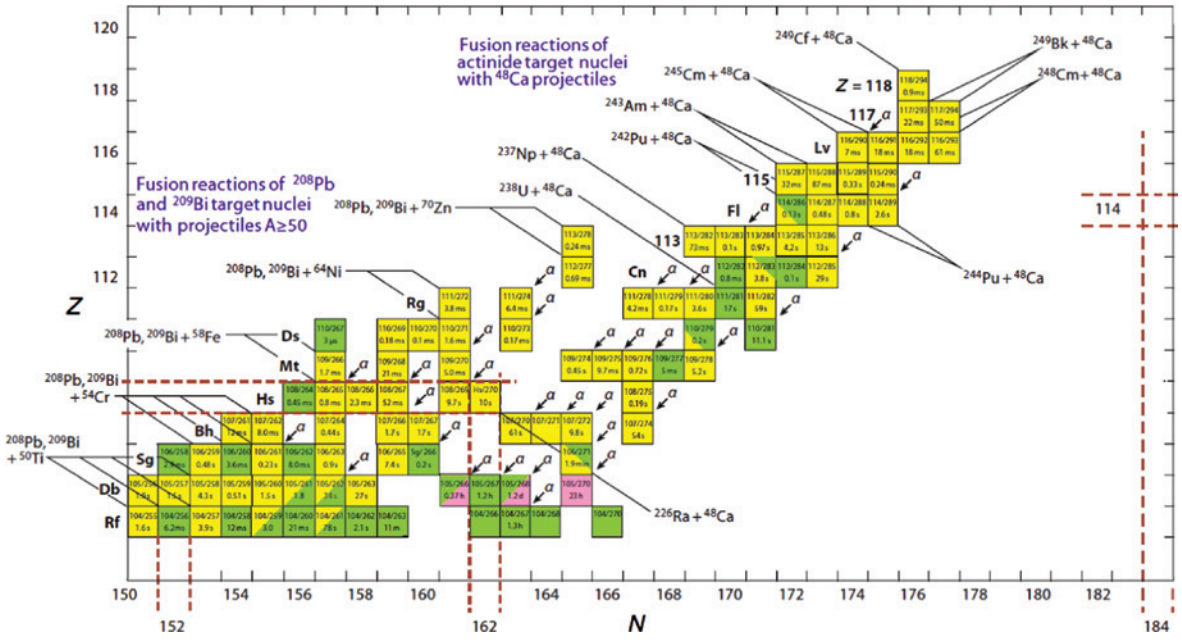


**Fig. 1:** Map of the region of super heavy nuclei relevant to this report including the reactions used to synthesize the various nuclides. (Adapted from [6].) The colors indicate different decay modes for nuclide $Z/A$ along with its half-life in milliseconds (ms), seconds (s), minutes (m) or hours (h) following the convention and data in [6], *q.v.*

described by Wilk *et al.* [11]. Production was via the hot fusion $^{22}$Ne + $^{249}$Bk reaction, and the leading event had an α-particle energy of 9.29 MeV, within the RIKEN results, with an estimated half-life of 1–10 s. It was followed by a 28 s α-decay, not by spontaneous fission. The latter observation is in contrast to the RIKEN result.

PRIOR JWP ASSESSMENT: The work of the collaboration of Morita *et al.* [9, 10] is very promising but has not met the Criteria for discovery owing to the paucity of events, the absence of firm connection(s) to known nuclides, and the inconsistencies noted above.

An investigation by Qin *et al.* [12] in 2006 at the Heavy Ion Research Facility in Lanzho, People's Republic of China used the $^{243}$Am($^{26}$Mg,3n)$^{266}$Bh reaction to produce four chains with a 1 s lifetime and $^{266}$Bh alpha energy (9.03 ± 0.08) MeV. These were followed by (8.53 ± 0.07) MeV alpha decays to a 37.5 s lifetime $^{262}$Db with one of the four chains continuing to $^{258}$Lr in 5.07 s with a 8.64 MeV alpha decay.

In 2007, the collaboration of Oganessian *et al.* [13] investigated the hot fusion of $^{48}$Ca with $^{237}$Np and reported two four-member α-decay chains commencing at $^{282}$113, passing through $^{278}$Rg, $^{274}$Mt, and $^{270}$Bh, and leading, in just one chain, to $^{266}$Db decay by spontaneous fission with a 32 min lifetime. The first two events in each chain showed excellent mutual agreement for both decay energies and lifetimes.[1] The third member gave lifetimes of 470 and 810 ms. None of the nuclides had been previously characterized.

PRIOR JWP ASSESSMENT: The 2004 collaboration of Oganessian *et al.* at Dubna was approximately contemporaneous with that of Morita *et al.* at RIKEN. The Dubna results in combination with the 2007 collaboration are encouraging but do not meet the Criteria for discovery because of the paucity of events, the lack of connections to known nuclides, and the absence of cross-reactions.

In 2009, Morita *et al.* used the fusion reaction $^{23}$Na + $^{248}$Cm to produce 16 persuasive chains of $^{266}$Bh providing a cross reaction to that alpha-emitting nuclide and its descendants in the $Z = 113$ alpha-decay chain [14]. The average alpha energy from $^{266}$Bh was 9.12 MeV. For seven of those, alpha decay to $^{262}$Db had an average 8.67 MeV energy and for four cases the chains continued to the 4.1 s alpha decay of $^{258}$Lr [15] with an average energy of 8.67 MeV all with excellent internal agreement and with the 2006 study of Qin *et al.* [12]. These agree with the

1 With low statistics, excellent agreement in lifetimes does not necessarily translate to high probability of a common radioactive decay origin. See K. H. Schmidt, *Eur. Phys. J.* **A 8**, 141 (2000).

previously determined property [15] of 4.1 s $^{258}$Lr decay (4 alpha branches between 8.59 and 8.68 MeV) and serves well to establish the $^{266}$Bh as a known anchor.

In 2012, the Morita *et al.* collaboration [16] repeated their earlier experiments and observed a third decay chain reportedly commencing with $^{278}$113. The properties of all three chains are reproduced in Fig. 2 below derived from [16].

In the case of Morita's $Z = 113$ chains, (the first two previously assessed as "inconsistent") the sum of the $\alpha_1$ and $\alpha_2$ energies is nearly the same, sidestepping the otherwise troublesome individual differences. Furthermore, the sum of $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$ energies is also nearly the same for the first and third chains,

left chain: Total energy in MeV is $(41.94 \pm 0.11)$
right chain: Total energy in MeV is $(42.12 \pm 0.13)$

signaling that the chains reasonably start and end up at the same states in the same nuclides. This appears to indicate that the starting and finishing states in the transition from $^{278}$113 to $^{262}$Db are the same in the two chains, even if different states are involved in the decays in between. This approach, although not decisive, can be applied to many odd-nuclei examples and its success is a sufficient, *but not necessary* condition for supporting consistency where it might be concealed by decays through a choice of intermediate states particularly when few events are recorded. We note that the total decay chain energies are not guaranteed to agree as in some cases gamma ray and/or conversion-electron energies may not be recorded and that these totals, although not imperative, can prove useful.

An important consideration is if the observed chains of Morita *et al.* are convincingly anchored to known nuclides. This is demonstrated in the Table 2 confirming that the 2012 decays $\alpha_5$ and $\alpha_6$ are in concordance with other determinations: the $^{266}$Bh study by Morita *et al.* using the $^{23}$Na + $^{248}$Cm fusion reaction and the decay of $^{262}$Db summarized in the 2001 Nuclear Data Sheets Akovali [15].

Conclusion: The observed $Z = 113$ $A = 278$ chain decay energies for $^{262}$Db ($\alpha_5$) and $^{258}$Lr ($\alpha_6$) are consistent with those measured in the Morita *et al.* (2009) $^{266}$Bh study and with values observed earlier by others [15]. Also, the lifetime values (not shown here) given in Morita *et al.* (2012) were consistent with the lifetimes

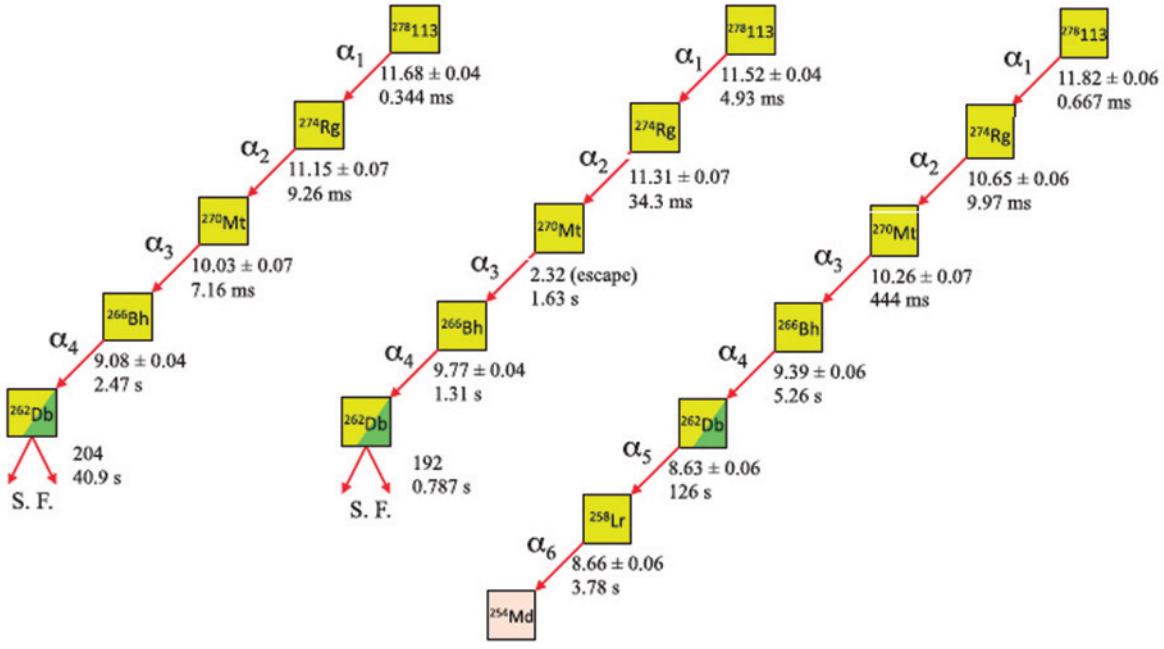


**Fig. 2:** Summary of the $Z = 113$ decay chains observed by the Morita *et al.* collaborations (*q.v.*). Values are $E_\alpha$/MeV above lifetimes in milliseconds (ms) or seconds (s).

**Table 2:** Alpha decay properties of the descendants of $^{266}$Bh.

| | | | Energy/MeV |
|---|---|---|---|
| **All energies in MeV** | **Morita *et al.* [14] (averages) $^{266}$Bh study** | **$Z = 113$ right chain** | **Akovali [15] nucl. data sheets** |
| $^{262}$Db $\alpha_5$ | 8.54 ~ 8.74 | 8.63 ± 0.06 | 8.45 ± 0.02 |
| | | | 8.53 ± 0.02 |
| | | | 8.67 ± 0.02 |
| $^{258}$Lr $\alpha_6$ | 8.60 ~ 8.71 | 8.66 ± 0.06 | 8.59 ± 0.02 |
| | | | 8.62 ± 0.02 |
| | | | 8.65 ± 0.02 |
| | | | 8.68 ± 0.02 |

measured previously [15]. All the "inconsistencies" pointed out in the previous JWP ASSESSMENT except for the missing $\alpha_3$ energy in the second chain have been resolved.

JWP ASSESSMENT: Three chains of $^{278}$113 observed by the RIKEN collaborations, the first in 2004 [9], the second in 2007 [10], and the third in 2012 [16], are now construed as being consistent. Firm connection to established nuclides is provided. The remaining criterion achieved for acknowledgement of discovery is an identification of $Z$ which is now embodied in the cross reaction production and characterization of the chain beginning with $^{266}$Bh as found by the RIKEN collaboration in 2009 [14] and by Qin *et al.* in 2006 [12]. The Criteria for discovery have been met.

The 2010 collaboration of Oganessian *et al.* [17–19] used hot fusion $^{249}$Bk($^{48}$Ca, $x$n) reactions to produce 5 alpha-decay chains originating with $^{293}$117 passing through $^{285}$113 and one additional chain from $^{294}$117 passing through $^{286}$113. In 2012 [20] and 2013 [21], Oganessian *et al.* used the $^{243}$Am($^{48}$Ca,2n) reaction to observe $^{289}115 \rightarrow {}^{285}113$, a cross reaction verification of identifying $^{285}$113. But because the earlier collaboration discovery claims for $^{282,283,284}$113 are different from the newly identified $^{285,286}$113, these do not serve to confirm the earlier priority claims.

The 2013 collaboration of Oganessian *et al.* [21] used the hot fusion $^{243}$Am($^{48}$Ca, $x$n) reactions to produce 24 persuasive alpha-decay chains originating with $^{288}$115 passing through $^{284}$113, 4 alpha-decay chains originating with $^{289}$115 passing through $^{285}$113, and one incomplete chain from $^{287}$115 passing through $^{283}$113. Complementary to this, the 2013 collaboration of Rudolph *et al.* [22] used the same reaction at GSI (Darmstadt) to produce 6 complete chain sequences in excellent agreement with the Dubna Oganessian collaborations. Despite the relatively large productivity, the energy dependence providing a picture of the excitation function is not illuminating. That is, "a yield curve: production cross section as a function of energy of the particle impinging upon a target nucleus" [1] was not considered statistically compelling.

The 2013 Oganessian collaboration [21] and the 2013 Rudolph collaboration provide redundancy to the three $^{284}$113 chains observed in 2004 with the alpha energies being in excellent agreement among most of the events. Table 3 and 4 summarizes alpha energies in MeV for the 24 and six events in the 2013 experiments and the three events from the earlier experiment.

Much of the minor discrepancies in energy are accommodated when sums are considered.

**Table 3:** Comparison of the observed alpha-particle energies (in MeV) for the chain members beginning with $^{288}$115.

| | | | | Energy/MeV |
|---|---|---|---|---|
| **Chain nuclide** | **Decay** | **$^{48}$Ca + $^{243}$Am (2013) [21]** | **$^{48}$Ca + $^{243}$Am (2004) [8]** | **$^{48}$Ca + $^{243}$Am (2013) [22]** |
| $^{288}$115 | $\alpha_1$ | 10.46 ± 0.07 | 10.46 ± 0.06 | 10.41 ± 0.07 |
| $^{284}$113 | $\alpha_2$ | 9.97 ± 0.13 | 9.84 ± 0.26 | 9.84 ± 0.33 |
| $^{280}$Rg | $\alpha_3$ | 9.70 ± 0.17 | 9.74 ± 0.02 | 9.77 ± 0.02 |
| $^{276}$Mt | $\alpha_4$ | 9.60 ± 0.23 | 9.73 ± 0.06 | 9.68 ± 0.15 |
| $^{272}$Bh | $\alpha_5$ | 9.03 ± 0.14 | 9.07 ± 0.11 | 8.95 ± 0.19 |
| $^{268}$Db | SF | Lifetime = 27 h | Lifetime = 16 h | Lifetime = 50 h |

**Table 4:** Energy sum combinations (in MeV) for sequential alpha decay pairs. See text.

| | | | Energy/MeV |
|---|---|---|---|
| **Chain** | **$^{48}$Ca + $^{243}$Am (2013) [21]** | **$^{48}$Ca + $^{243}$Am (2004) [8]** | **$^{48}$Ca + $^{243}$Am (2013) [22]** |
| $\alpha_1 + \alpha_2$ | 20.44 ± 0.03 | 20.30 ± 0.32 | 20.24 ± 0.33 |
| $\alpha_2 + \alpha_3$ | 19.67 ± 0.04 | 19.59 ± 0.47 | 19.61 ± 0.33 |
| $\alpha_3 + \alpha_4$ | 19.31 ± 0.09 | 19.48 ± 0.33 | 19.45 ± 0.13 |
| $\alpha_4 + \alpha_5$ | 18.65 ± 0.11 | 18.80 ± 0.07 | 18.63 ± 0.27 |

However, the Criteria (*q.v.* [1]) have not been met as there is no mandatory identification of the chain atomic numbers neither through a known descendant nor by cross reaction. Chemical determinations as detailed in the subsequent profile of $Z = 115$ where they are documented, serving the important role of assigning atomic number are insufficiently selective although certainly otherwise informative.

JWP ASSESSMENT: The 2004 collaborations of Oganessian *et al.* at Dubna and those of Morita *et al.* at RIKEN were published on 2 February and 15 October, respectively. Recent results from the RIKEN group have cross reactions that support anchoring their claims to known atomic numbers. For Dubna, many alpha-decay chains from the $^{243}$Am($^{48}$Ca,3n)$^{288}$115 fusion serve to duplicate and reinforce the characteristics assigned to $^{284}$113 observed earlier. But, the 2004 and 2007 Dubna physical measurements were not able to within reasonable doubt determine $Z$. Chemistry probes that had been employed in previous experiments remain unpersuasive in their ability to assure the $Z$ value. (Details are discussed below in the consideration for $Z = 115$.) No new chemistry separations or simulations have been instituted to nullify that JWP criticism although preliminary studies have been done to explore alternatives [23]. We conclude the Criteria for discovery have not been met by the Dubna-Livermore group claims for $Z = 113$ while the RIKEN claim does meet the Criteria. Priority for the discovery has been fulfilled by the RIKEN collaboration.

## 3.2 $Z = 115$

The 2004 collaboration of Oganessian *et al.* [8] which was mentioned in the $Z = 113$ discussion above reports one chain commencing with $^{287}$115. In this same fusion experiment, at a slightly lower beam energy and the same beam dose, three new consecutive α-decay chains were reported assigned to the $^{288}$115 isotope and products $^{284}$113, $^{280}$Rg, $^{276}$Mt, and $^{272}$Bh with agreement among the five sets of α-particle energies and among the five lifetime values. All terminated in a approximately 26 h spontaneous fission lifetime assigned to $^{268}$Db. All five nuclides were reported for the first time.

The collaboration of Dmitriev *et al.* [24, 25] at the Flerov Laboratory in Dubna used the $^{48}$Ca + $^{243}$Am fusion reaction in 2005 to produce 15 additional spontaneous fission nuclides and other reaction products recoiling directly, without selectivity, onto a copper surface from which they were extracted and subjected to cation exchange separation. The technique employed was claimed to distinguish between Group 3 elements (lanthanides and actinides) and combined Groups 4 and 5. Theoretical expectations were proposed for discounting Group 4, corresponding to Rf spontaneous fission. Yet, theoretical predictions were also noted for the *possible* inversion of the sequence of trends in a periodic group amongst the heavy elements. The mean lifetime for the assigned spontaneous fission averaged 46 h for the 15 nuclides, a value within statistical agreement with the first determinations by Oganessian *et al.* [8].

In 2007, the Livermore-Dubna collaboration of Stoyer *et al.* [26] published their production of $^{288}$115 from the $^{48}$Ca + $^{243}$Am fusion reaction recoiling directly onto a copper surface and to extract the terminal, long-lived $^{268}$Db for revised chemical separation procedures. Two procedures were employed, each aimed at separating Group 4 from Group 5. A total of five spontaneous fission events were observed with lifetimes of 16–37 h. In those separations that were also able to distinguish between Nb and Ta-like chemical behavior, all three such events appeared in the Ta-like fractions.

PRIOR JWP ASSESSMENT: The Dubna–Livermore collaborations have reported a total of 23 events assigned either directly or indirectly to $^{288}115$ via a single target-projectile combination. The assignment is supported mostly by chemical studies of the terminal spontaneous fission assigned to $^{268}$Db. Those chemical studies serve a central role in whether or not the Criteria of identification have been met. No carrier-free actinide tracers were employed despite the extremely complex oxidation chemistry and adsorption quirks of those Group 3 elements in contrast to lanthanide behavior. Chemical properties of confirmed heavy elements are important for improving relativistic theories of chemical behavior. However, by itself, current theory is sufficiently uncertain that it cannot be used to distinguish the properties of Groups 4 and 5 elements in this region with confidence.

In 2007, one-and-a-half years after the Dubna–Livermore [26] experiments, the chemically separated samples assigned in 2005 as dubnium were measured for very long periods of time in an alpha spectrometer by a group at Livermore [27]. The alpha spectra revealed the presence of Am, Cm and Po isotopes, the latter presumably produced by transfer reactions on Pb impurities in the target or target backing. A Dubna study of one 2-year-old counting sample by Dressler *et al.* [28] found alpha activity due to some americium isotopes but no evidence of spontaneous fission activity during very long counting times. Despite separations designed to occlude interferences, the extraordinarily low event rates and as yet not perfected chemistries counsel the need for extreme caution in the face of uncertain chemical purity.

The 2007 collaboration of Oganessian *et al.* [13] reported the observation of two decay chains originating from $^{282}113$ produced in the hot fusion $^{237}$Np($^{48}$Ca,3n) reaction. This does not overlap with the $^{287}115$ and $^{288}115$ originating $Z = 113$ decays observed earlier from hot fusion $^{243}$Am($^{48}$Ca,4n) and $^{243}$Am ($^{48}$Ca,3n) reactions, respectively.

The 2012–2013 collaborations of Oganessian *et al.* [20, 21] produced a large number of five-membered chains again with the $^{48}$Ca + $^{243}$Am combination. Twenty-four chains beginning with $^{288}115$ decayed with alpha-particle emission of average energy (10.46 ± 0.06) MeV followed by the descendants listed in the previous table that agree with excellent precision with the 2004 results. In this collaboration [20, 21], four decay chains originating from $^{289}115$ were produced in the ($^{48}$Ca, 2n) reaction channel. These results are summarized by Oganessian *et al.* [21] and in Figure 3 below.

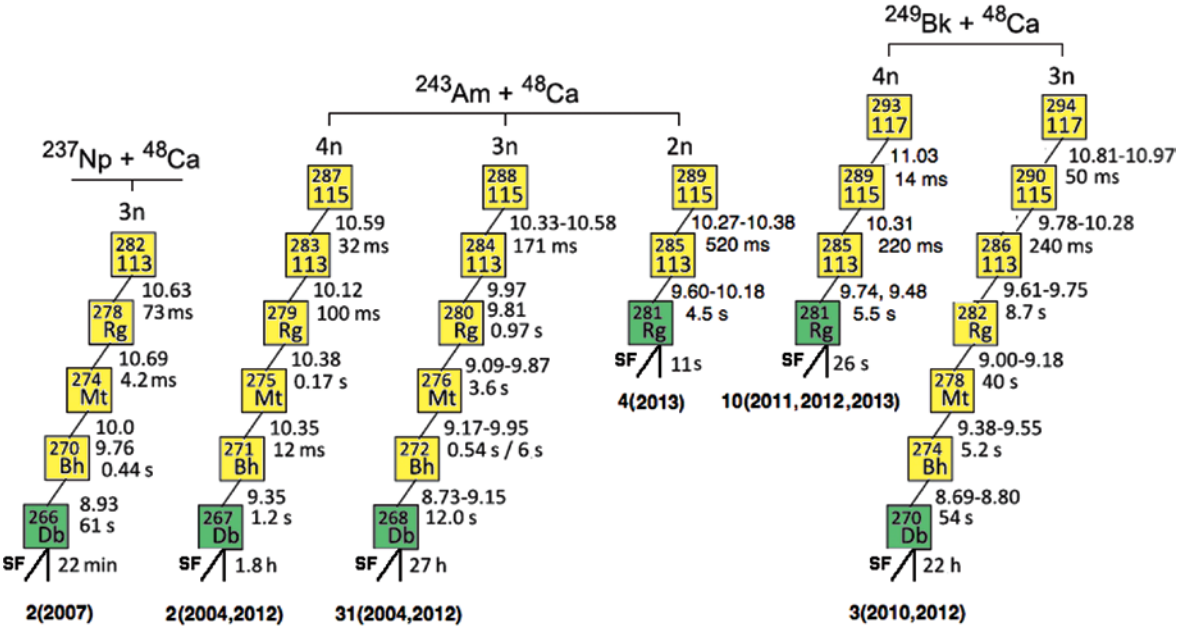


**Fig. 3:** Complete decay chains observed by Oganessian *et al.* derived and edited from figure 5 of that reference [21]. The number of events (publication dates) in bold at the bottom corresponds to those recognized by the JWP as persuasive. For each isotope $E_\alpha$/MeV and lifetimes in milliseconds (ms), seconds (s) or hours (h) are shown.

CHEMISTRY: An essential issue for the JWP's consideration was that if the chemical behavior could be unequivocally assigned to $Z = 115$, that would have been a profound decider on the identity of its precursor chain members. A number of chemistry experiments were performed on the long-lived spontaneously fission product recovered from Ca + Am fusion reactions. Its half-life is approximately 26 h. However, the chemical properties of (Rf and) Db can be significantly different from their corresponding lighter congeners, Zr-Hf and Nb-Ta, respectively. Thus, the traditional simple congener principle may not be applied with robust confidence to identify Db. Use of relativistic modeling of chemical behavior to circumvent such departures is an extraordinary new venture and needs definitive observed behavior to bolster its applicability, but that theory-experiment convergence is still in the future for high-$Z$ elements despite success at lower atomic numbers.

Starting in 1988, a number of chemical studies of dubnium were performed in which about 30 s half-life $^{262,263}$Db were both unquestionably produced by the $^{249}$Bk($^{18}$O,$x$n) reactions in which $x = 4$ and 5. These investigations looked at the extraction of Db in strong acid organic ligand partitions, the latter being methyl isobutyl ketone [29], diisobutylcarbinol [30], triisooctylamine [31], Aliquat 336 [32], and in cation exchange using α-hydroxyisobutyric acid [33]. As in all of the published separation schemes, radiotracers are added to follow congeners niobium and tantalum and lanthanide radiotracers serve as proxies for actinide behavior. But the lanthanides chosen are restricted to those with 3+ oxidation states yet actinides and some lanthanides are commonly found in 4+ or 5+ states. Furthermore, the actinide protactinium has sometimes, but not always, been used as a quasi-homologue of a Group 5 element. In the separation studies, dubnium at times behaves more like protactinium than like either niobium or tantalum. What is seen is that even in the $^{18}$O-irradiation investigations where Db is definitely identifiable the possibility of interferences has not been eliminated. A 2005 study by Schumann *et al.* [34] employed a wide range of tracers including from Groups 6 and above to serve as homologues of heavier transactinide congeners (despite recognition that relativistic effects can frustrate such expectations). One of the observations of that study was that a single initial precipitation step in the dubnium separations was contaminated by a variety of elements expected to have been occluded. Wilk *et al.* [35] sought to improve the separation scheme employed by Stoyer *et al.* [26] and encountered Nb and Ta both evincing two behaviors which could not be explained although the authors did suspect that this was evidence for different speciation of both the Nb and Ta in the solutions employed. The existence of a variety of halide, oxyhalide, and hydroxyhalide forms for the heavy Group 5 elements has been acknowledged as a complicating factor in their chemistries [36–38]. The chemistry employed in the $Z = 115$ studies seeking to prove the identity of dubnium did not employ the same steps as in the definitive studies on the short-lived $^{262}$Db and $^{263}$Db.

The Oganessian collaborations of 2010 studied the $^{48}$Ca + $^{249}$Bk fusion reactions to form $Z = 117$ products [17, 18]. Three of the chains from the 4n evaporation channel included descendants $^{289}$115 and $^{285}$113. One transitioned through $^{290}$115 and $^{286}$113. The 2012 results of Oganessian *et al.* [20] for $^{48}$Ca + $^{243}$Am included one chain through $^{289}$115 and $^{285}$113 from the 2n evaporation channel and subsequently a total of four inclusive chains from the 2n evaporation channel were found in 2013 [21]. The average alpha-particle energies observed are presented in Table 5. Consequently, cross reactions show assigned decay characteristics of $^{289}$115(α) → $^{285}$113(α) → $^{281}$Rg(SF) observed in the $^{243}$Am($^{48}$Ca,2n) reaction (4 events) agree well with the assigned decays originating from $^{293}$117 observed in the $^{249}$Bk($^{48}$Ca,4n) reactions (6 events).

The 2013 GSI collaboration of Rudolph *et al.* [22] studied the $^{243}$Am + $^{48}$Ca reactions. They reported the observation of 22 more decay chains originating from $^{288}$115 produced by the 3n evaporation channel terminating in the spontaneous fission of $^{268}$Db and one of $^{287}$115 by the 4n evaporation channel. Those reinforce the results of the Russia–US collaboration [21]. The same collaboration attempted to measure coincident X-rays whose assignment property would have been a significant boost to confidence in $Z$ identification which is lacking in the Am + Ca production channel. The use of X-rays for elemental identification is complicated by the fact that the observed photons, expected to have very precise X-ray energies, might be γ-rays or Compton scattering or background events. Given the low number of photons detected at the predicted X-ray transition energies and the presence of other X-rays or γ-rays in the spectrum, the X-ray identification was not regarded as persuasive. The paper was able to demonstrate the coincidence between alpha decay and gamma-ray emission in the decays of $^{280}$Rg and $^{276}$Mt, which confirms the population of excited states in alpha decay of odd-$Z$ super heavy nuclides.

**Table 5:** Comparison of alpha-particle decay chains with $E_\alpha$/MeV and half-lives in seconds (s) or hours (h) beginning with $^{293}$117 and $^{294}$117.

| | | | | | Eα/MeV |
|---|---|---|---|---|---|
| | | | | $^{48}$Ca + $^{249}$Bk | $^{48}$Ca + $^{243}$Am |
| | Decay | 2010 (3 events) [17] | 2012 (3 events) [19] | 2013 (4 events) [39] | 2013 (4 events) [21] |
| $^{293}$117 | $\alpha_1$ | 11.03 ± 0.08 | 10.80 ± 0.07 | 11.10 ± 0.09 | |
| $^{289}$115 | $\alpha_2$ | 10.31 ± 0.09 | 10.26 ± 0.07 | 10.46 ± 0.15 | 10.40 ± 0.08 |
| $^{285}$113 | $\alpha_3$ | 9.74 ± 0.08 | 9.63 ± 0.18 | 9.85 ± 0.04 | 9.89 ± 0.16 |
| $^{281}$Rg | SF/$\alpha_4$ | 26 s | 51 s | 9.32 ± 0.04 | 16 s |

| | | | | $^{48}$Ca + $^{249}$Bk |
|---|---|---|---|---|
| | Decay | 2010 (1 event) [17] | 2012 (2 events) [19] | 2014 (2 events) [40] |
| $^{294}$117 | $\alpha_1$ | 10.81 ± 0.10 | 10.96 ± 0.07 | 11.05 ± 0.04 |
| $^{290}$115 | $\alpha_2$ | 9.95 ± 0.40 | 10.02 ± 0.26 | 10.26 ± 0.03 |
| $^{286}$113 | $\alpha_3$ | 9.63 ± 0.10 | 9.68 ± 0.11 | 9.3 ± 0.3 |
| $^{282}$Rg | $\alpha_4$ | 9.00 ± 0.10 | 9.11 ± 0.20 | 8.96 ± 0.03 |
| $^{278}$Mt | $\alpha_5$ | 9.55 ± 0.19 | 9.39 ± 0.07 | 9.46 ± 0.03 |
| $^{274}$Bh | $\alpha_6$ | 8.80 ± 0.10 | 8.74 ± 0.05 | 8.82 ± 0.25 |
| $^{270}$Db | SF/$\alpha_7$ | 23 h | 30 h | 7.90 ± 0.03 |
| $^{266}$Lr | SF | | | 16 h |

The energy sums for the entire six-membered alpha chains above are 57.74, 57.90 and 57.85 MeV, respectively.

JWP ASSESSMENT: The 2010 [17, 18] jointly with the 2013 [21] collaborations of Oganessian *et al.* have met the Criteria for discovery of the element with atomic number $Z = 115$ in as much as the reproducibility of alpha chain energies and lifetimes of $^{289}$115 in a cross reaction comparison is very convincing.

### 3.3 $Z = 117$

In 2010, the Russia-US collaboration of Oganessian *et al.* [17, 18] used the $^{48}$Ca + $^{249}$Bk fusion reaction to produce the compound nucleus $^{297}$117 leading to three complete four-member chains commencing with $^{293}$117 and one seven-member chain commencing with $^{294}$117 the last member of each ending with spontaneous fission. In 2012 a second series of $^{48}$Ca + $^{249}$Bk fusions to form the compound system $^{297}$117 were studied [19] resulting in three more four-member chains commencing with $^{293}$117 and two more seven-member chains commencing with $^{294}$117. Four more complete chains were measured by Oganessian *et al.* in 2013 including a new alpha decay from two of the events containing $^{281}$Rg [39]. As noted in discussion of $Z = 115$, the $^{48}$Ca + $^{243}$Am fusion reported by Oganessian *et al.* to have produced four short chains of $^{289}$115 [21] agrees with the daughter events from $^{293}$117 decay within the precision of the alpha-particle energies [17–19, 39]. That cross reaction comparison is included in the table below.

JWP ASSESSMENT: A convincing case in cross reaction producing $^{289}$115 and $^{285}$113 from both $^{48}$Ca + $^{249}$Bk and $^{48}$Ca + $^{243}$Am is demonstrated in the top of the previous table. Thus, the 2010 [17, 18], 2012 [19] and 2013 [39] jointly with 2013 [21] collaborations of Oganessian *et al.* have met the Criteria for discovery of the elements with atomic numbers $Z = 115$ and $Z = 117$.

## 4 Comments

The certainty of the assignments of the new elements with atomic numbers 113, 115, and 117 is strengthened by the nature of the experimental technique, where the atomic number is assigned by a chain of correlated

(in time and position) alpha decays that have a vanishingly small probability to be random coincidences. When corresponding chains are observed in cross reactions of (X,2n), (X,3n) and (X,4n) reactions and/or in the decays of heavier elements made at more than one laboratory, the assignments are made beyond a reasonable doubt.

The new elements identified in the claims considered here have distinct features from their assigned $Z = 114$ and $Z = 116$ neighbors [5]. The nature of the alpha energy spectra observed in the decays of nuclides with atomic numbers 113, 115, and 117 differ from their even-$Z$ neighbors and show a wider energy spread corresponding to decay to excited states. This is further evidence that new atomic number has been produced in these studies and disfavor charged-particle emission in the evaporation process or electron capture in the decay chains. As a result a large group of super heavy nuclides are now on an island without connection to the main peninsula of known nuclei where reliable identification of $Z$, $N$ becomes more and more difficult. Firmly connecting this island to the nuclear mainland should remain a priority. We encourage development of direct physical methods to determine $Z$. Particularly promising are the prospects for X-ray measurements and identification as was now attempted [22].

In light of the utility of applying the sum energy check for odd nuclei alpha energies and check of consistency of lifetimes, research groups are encouraged to publish or make readily available the decay data for individual events and not just report averages or mean lifetimes. In addition, research groups are encouraged to make readily available all the raw data (alpha energies, lifetimes, etc.), no matter how well or poorly they fit to a claimed level scheme.

Should the recommendations of the JWP prove, through future experiments, to be subject to reversal, there should be no issue with authorizing revisions as this has occurred in the past, *viz* with nobelium.

## 5 Summary of JWP conclusions

Criteria for the discovery of new elements have been met for elements with atomic numbers $Z = 113$, 115, and 117. The RIKEN collaborations of Morita *et al*. [9, 10, 14, 16] have fulfilled the Criteria for their discovery of element 113. The Dubna–Livermore–Oak Ridge collaborations of Oganessian *et al*. 2010 [17, 18], 2012 [19] and 2013 [39], jointly with 2013 [21] are credited with the discoveries of elements 115 and 117.

## 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).

2014–2015: President: Reedijk, Jan (Netherlands); Vice President: Öhrström, Lars (Sweden): Secretary: Leskelä, Markku (Finland); Past President: Loss, Robert D. (Australia): Titular Members: Ding, Tiping (China/Beijing); Drábik, Milan (Slovakia); Rabinovich, Daniel (USA); Tshuva, Edit Y. (Israel); Walczyk, Thomas R. (Switzerland); Wieser, Michael (Canada); Associate Members: Buchweishaija, Joseph (Tanzania); García-Martínez, Javier (Spain); Karen, Pavel (Norway); Kiliç, Adem (Turkey); Sakai, Ken (Japan); Vannier, Rose-Nöelle (France); National Representatives: Trendafilova, Natasha (Bulgaria); Prugovečki, Biserka (Croatia); Mathur, Sanjay (Germany); Chandrasekhar, V. (India); Armaleo, Lidia (Italy); Abdul Aziz,

Yang F. (Malaysia); Badshah, Amin (Pakistan); Correira, João Galamba (Portugal); Kalmykov, Stepan N. (Russia); Meesuk, Ladda M. (Thailand).

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