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# Discovery of the elements with atomic numbers greater than or equal to 113 (IUPAC Technical Report)*

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*Abstract*: The IUPAC/IUPAP Joint Working Party (JWP) on the priority of claims to the discovery of new elements 113–116 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 1992 IUPAC/IUPAP Transfermium Working Group (TWG), and reinforced in subsequent IUPAC/IUPAP JWP discussions, it was determined that the Dubna-Livermore collaborations share in the fulfillment of those criteria both for elements $Z = 114$ and 116. A synopsis of experiments and related efforts is presented.

*Keywords*: atomic number 114; atomic number 116; discovery; new elements; IUPAC Inorganic Chemistry Division; IUPAP; periodic table; trans-copernicium; transfermium.

## INTRODUCTION

The working party of independent experts drawn from IUPAC and IUPAP that assigned priority of claims to the discovery of element 112 [1] has also addressed recent results of experiments seeking yet heavier elements. As usual, 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 30 June 2007. Within the JWP, much of the extensive preliminary review was conducted amongst members via electronic communications. In May 2008, the JWP met for three days in Vancouver, Canada and was joined by Prof. John Corish, former President of the Inorganic Division of IUPAC, as an observer of the group's proceedings. The mandate of the working party was to review documentation, to make judgments on the priority claims, and to report to the two Unions through Prof. Corish. Following the meeting, the JWP sought additional clarification of some of the references in hand. Further, the JWP requested that the deadline be extended to 31 July 2008 in order to accommodate already-published documentation relevant to the submitted claims of discoveries of elements with atomic numbers $Z = 113$–116 and 118. It did not entertain post-deadline submissions, published or otherwise.

*Sponsoring bodies: IUPAC Inorganic Chemistry Division; International Union of Pure and Applied Physics; see more details on page 1494. The members of the IUPAC/IUPAP JWP are the authors of this report.

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It is not the intent of the JWP to influence one way or another the otherwise independent refereeing of claims submitted to journals for review which constitute traditional assessment. In that regard, as we have emphasized in the past, much more credence is given to refereed work than to unvetted proceedings or reports. This report is not a comprehensive review and, for the most part, does not comment on studies unless directly germane to our deliberations.

## CRITERIA USED

Criteria that must be satisfied for the discovery of a new chemical element to be recognized [2,3] were delineated by the IUPAP/IUPAC Transfermium Working Group (TWG) in 1992 and have served as continuing guiding principles. Those references should be consulted by interested parties as the criteria serve, not to set a higher standard for "discovery" than applies elsewhere in science, but rather to describe a uniform, consistent basis for definitive observation and interpretation that is generally agreed to by investigators.

Sections particularly relevant to balancing a sensibly conservative stance with the need for reasonable flexibility continue to be paramount to our deliberations. A quintessential *waiver option* in the criteria has been italicized by us in the quoted selection below, for emphasis, as we have done in the past.

> "Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide...
>
> 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.*"

Factors which the JWP regard positively [4,5], at least to some extent, include low background events, cross-bombardments, excitation functions, internal reproducibility in productions and in decays, physicochemical behavior, spatial correlations of evaporations and subsequent decays, and separators distinguishing *Z*-values. When such favorable properties occur in combination, the case may be regarded as greatly strengthened. Factors that are deemed troublesome, but not necessarily exclusive, include missing anchors to known/familiar nuclei, irreproducibility, unconvincing chemistry, and high background situations.

We would like to point out that cross-bombardment experiments are now achieving increasing importance for the discovery of new superheavy elements. Sometimes such experiments, which might occur in the same laboratory, can provide the kind of corroboration that was previously sought by requiring independent experiments, preferably at different laboratories. Cross-bombardments were established as one of the criteria for discovery in 1991 by the TWG [2].

The key to this importance of cross-bombardment lies in the fact that, in both hot and cold *fusion*, the *Z* of the superheavy is reliably determined as the sum of the *Z*'s of the target and projectile. The neutron number of the superheavy may vary but not the proton number. At present this has been empiri-

cally established by the many fusion events that have been presented to us and supported by nuclear reaction theories.

That no proton emission accompanies fusion events may not be very surprising. When the compound nucleus of a superheavy is formed, the temperature of the system is typically an MeV or less, while the barrier for proton emission is at least an order of magnitude larger. Thus, more than negligible proton evaporation has not been observed and, typically, only a few neutrons are evaporated. However, it would be comforting for the absolute establishment of the insignificance of proton emission, to have more experimental evidence. To exclude the possibility that a proton might be stripped from the projectile (or the target) in the same event in which a superheavy is subsequently produced by fusion cannot be eliminated. In hot fusion, there are several factors that make any such stripping event somewhat more probable than in cold fusion. Both the slightly higher energy of the projectile and its lighter mass conspire to give the bombarding protons higher velocity and greater likelihood of being stripped. Further, the lesser binding of the protons in the lighter projectile (where the Coulomb barrier is less) for hot fusion would seem to make its detachment more likely. We are already comforted by the empirical evidence of the lack of proton emission in fusion reactions discussed below and in other very limited experimental evidence [6,7] but would welcome further study of the matter. Finally, confidence in the *Z*-assignment is reinforced by cross-bombardments that involve both even–even and even–odd mass or atomic number combinations.

## DISCOVERY PROFILES

As in previous reports, we follow the procedures for discovery profiles. Each concise profile begins with a reprise of the pertinent content from earlier reports [1,3,4,5] if any. The element atomic number is in boldface followed by sequentially enumerated comment labels, which are in chronological order. An historical account of the relevant publications on each element is given with our consensus opinion(s) appended as to the value of the evidence on the basis of the criteria. Our resources were articles submitted by 31 July 2008 by research groups and laboratories in response to formal solicitations by IUPAC. Also, other relevant publications routinely available in research libraries or through modern electronic search techniques were sought. A listing appears at the end of this report. Subsequent literature, some of which is undoubtedly quite relevant to conclusions herein, nevertheless has not been included in this report.

### *Z* = 113

#### ***113;*** *01 The collaboration of Oganessian et al. [8,9]*

In 2004, this collaboration studied the hot fusion reaction of $^{48}$Ca with $^{243}$Am and reported 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 α-decay was inferred to lead to $^{267}$Db which decayed by spontaneous fission (with a 100 min lifetime). At a different bombardment energy, three chains beginning with $^{288}$115, continuing sequentially to $^{284}$113, $^{280}$Rg, $^{276}$Mt, $^{272}$Bh, and terminating with spontaneous fission of $^{268}$Db with mean lifetime of 23 h were observed with good internal agreement. None of the nuclides had been previously characterized.

#### ***113;*** *02 The collaboration of Morita et al. [10,11]*

Production of two chains of α-emitting nuclides was reported by Morita et al. from the cold fusion reaction of a bismuth target with a $^{70}$Zn beam at the RIKEN heavy-ion facility in Japan, the first in 2004 [10] and the second in 2007 [11]. 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 significantly different (41 vs. 0.8 s). For both chains, position-sensitive detectors were used. 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 systems. But a single report of a triple-coincidence of α-emitters commencing with $^{266}$Bh has been described by Wilk et al. [12]. 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 uncertainties of the RIKEN results, with a lifetime 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.

JWP ASSESSMENT: The work of the collaboration of Morita et al. 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.

#### ***113;*** *03 The collaboration of Oganessian et al. [13]*

In 2007, this collaboration 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. The third member gave lifetimes of 470 and 810 ms. None of the nuclides had been previously characterized.

JWP ASSESSMENT: The collaborations of Oganessian et al. at Dubna were essentially contemporaneous with those of Morita et al. at RIKEN. The results 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-bombardments.

### ***Z*** **= 115**

#### ***115;*** *01 The collaboration of Oganessian et al. [8,9]*

The Oganessian collaboration [8,9] from **113;** 01 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 ≈26 h spontaneous fission assigned to $^{268}$Db. All five nuclides were reported for the first time.

#### ***115;*** *02 The collaboration of Dmitriev et al. [14,15]*

The collaboration of Dmitriev et al. [14,15] at the Flerov Laboratory in Dubna used the $^{48}$Ca + $^{243}$Am fusion reaction in 2004 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 chemical separations. 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. The paper notes the peculiar fact that all 15 events occurred in the first 174 h of measurement and no events occurred in the next 783 h.

#### ***115;*** *03 The collaboration of Stoyer et al. [16]*

In 2005, the Livermore Flerov collaboration of Stoyer et al. [16] undertook to produce more $^{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.

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.

## *Z* = 114, 116, and 118

These profiles actually begin with element 112, copernicium, because it is linked crucially to the profiles of the higher elements. Previous consideration of a collection of results reported to involve $^{283}$Cn, arose from cross-bombardments interpreted as either direct to element 112 or to even higher *Z* elements that subsequently decay through element 112. In that regard, the discussion of cross-bombardment results leading to acceptance of $^{283}$Cn proves to be pivotal in the subsequent consideration of even heavier elements and deserves careful deliberation.

Moreover, the history of these studies is a useful venue for demonstrating the rationale for the JWP's necessarily conservative stance in drawing conclusions. One could paraphrase the introduction to the most recent publication [17] as follows. Three years after the first Hofmann et al. experiments, Dubna reported the production of $^{283}$Cn with a spontaneous fission half-life of 3 min [18]. Subsequent production experiments enabled chemical studies to show the elemental product was not mercury-like. In retrospect, identification of 112 was acknowledged to be tentative because it relied on *nonspecific spontaneous fission detection* (italics by the JWP). Further experiments indicated a 4-s half-life associated with a 9.5 MeV α-decay, but production attempts at Berkeley [19] failed to reproduce the observation. Chemistry experiments in Germany failed to observe element 112 [20]. To confound the situation, there was no anchor tying $^{283}$Cn to any known nuclide. Further developments followed these experiments.

### ***112;*** *01 The collaborations of Oganessian et al. [21,22]*

These collaborations used the reactions $^{48}$Ca + $^{242}$Pu and $^{48}$Ca + $^{244}$Pu, each to make one observed chain stated to originate with $^{287}114$ and $^{289}114$, respectively, which passed through unknown intermediates, $^{283}$Cn and $^{285}$Cn, and terminated in spontaneous fission at $^{283}$Cn and $^{277}$Hs.

### ***112;*** *02 The collaboration of Oganessian et al. [18]*

This Dubna collaboration used the reaction $^{48}$Ca + $^{238}$U and reported two events which decayed by spontaneous fission with a lifetime of ≈2 min and were ascribed to $^{283}$Cn. An independent repeat of the same experiment [19] did not show any events, albeit with insufficient sensitivity to disprove the data from [18]. Another independent attempt to follow the chemistry of element 112, produced by the same path, led to several events assigned to $^{283}$Cn [23] and were observed to follow radon-like, i.e., non-mercury-like, behavior.

### ***112;*** *03 The collaborations of Oganessian et al. [24,25] and [26,27]*

In the Oganessian et al. collaborations [24,25] and [26,27], $^{244}$Pu + $^{48}$Ca, in the first case and $^{248}$Cm + $^{48}$Ca, in the second case, were used to produce decay chains reported to commence with $^{288}114$ or $^{292}116$, respectively, and were followed by a pair of concordant α-decays, assigned to the otherwise unknown $^{284}$Cn, and terminating in spontaneous fission of unknown $^{280}$Ds. The decay energies and lifetimes of five events for $^{284}$Cn are internally redundant, but no docking to recognized nuclei

occurred. In the $^{244}$Pu + $^{48}$Ca study [22,25], another event, originating with $^{289}$114 and followed by a chain observed reportedly through $^{285}$Cn and $^{281}$Ds, terminated with spontaneous fission at $^{277}$Hs, with all of these nuclides unknown. The experiment in [22,25] is discussed further in [26–28].

***112;** 04 The collaboration of Oganessian et al. [29]*

The 2003 collaboration (published in 2004) sought to reproduce the 1998 claims to $^{283}$Cn synthesis by [18]. A 29-day irradiation of $^{238}$U with a $^{48}$Ca beam, having a mid-target energy of 231 MeV, produced no relevant decay chains, a result in common with that of Berkeley [19]. A second irradiation lasting 15 days at an energy of 234 MeV produced two spontaneous fission events with a lifetime of about 14 min, a value consistent with the 1998 values claimed for eka-Hg-daughter $^{283}$Cn decay [21]. No α-decay branches were measured.

***112;** 05 The collaboration of Oganessian et al. [28]*

The 2003 collaboration (published in 2004) utilized $^{48}$Ca reactions with both $^{244}$Pu and $^{245}$Cm to reach $Z$ = 114 and 116, respectively. Three observed chains (one from Pu, two from Cm) decay in ≈9 s by 9.5 MeV α-emission, all events being in agreement and assigned to $^{283}$Cn. The daughter nuclei in each case decay by spontaneous fission with an average lifetime of 0.4 s. The collaboration results involve both even–even and even–odd combinations of projectile-target mass numbers.

***112;** 06 The collaboration of Oganessian et al. [30]*

This collaboration continued generating $^{48}$Ca-induced fusion reactions with U, Pu, and Cm targets to produce $Z$ = 112, 114, and 116 isotopes. Fifteen observed chains pass through $^{283}$Cn, which decays with a lifetime of ≈6 s by 9.54 ± 0.06 MeV α-emission leading to $^{279}$Ds daughter nuclei, which in turn decay by spontaneous fission with an average 0.3 s lifetime. In two chains, $^{279}$Ds underwent α-decay with an energy of 9.7 MeV, followed by one or two more alphas and spontaneous fission assigned to $^{271}$Sg and $^{267}$Rf.

***112;** 07 The collaboration of Oganessian et al. [31]*

In 2006, this collaboration sought to synthesize superheavy elements by $^{48}$Ca-induced fusion reactions with $^{249}$Cf and $^{245}$Cm. In the latter case, one decay chain involved an intermediate $^{283}$Cn step with α-particle decay of 9.57 MeV, in excellent agreement with the previous accumulation of results, but with a lifetime of only 35 ms. The daughter $^{279}$Ds decayed in 0.7 s by 9.7 MeV α-emission in agreement with [30]. This particular chain terminated after 23 min with spontaneous fission attributed to $^{267}$Rf.

***112;** 08 The collaboration of Hofmann et al. [32]*

This GSI collaboration sought to re-attempt the synthesis of element 112 by the $^{48}$Ca + $^{238}$U fusion reaction that previously had evinced contradictory results [18–20,23,29]. They reported two events with α-energies of 9.52 MeV ascribed to $^{283}$Cn and two other events following a spontaneous fission branch. The $^{283}$Cn lifetime for the four events was 10 s.

JWP ASSESSMENT: Early reports on $^{283}$Cn were conflicted, and the discrepancies remain unexplained. The more recent Dubna collaborations [28–31] have performed careful, high-quality studies in which the synthesis of $^{283}$Cn is acknowledged with confidence*, given the significant redundancies at Dubna and the important independent investigation at GSI [32]. Although there remain unsecured connections to known descendents, we note that among the criteria established by the TWG is the following, addressing cross-bombardments: "Comparison of the probability of production of $^{A}Z$ in different combinations of target and projectile can sometimes give valuable assignment criteria." Collectively, the recent Dubna and GSI results above find reproducible decay characteristics from $^{48}$Ca fusion studies on

*In finalizing the draft of this Report, an additional independent confirmation of $^{283}$112 by the collaboration of Stavsetra et al. at Berkeley was published [34].

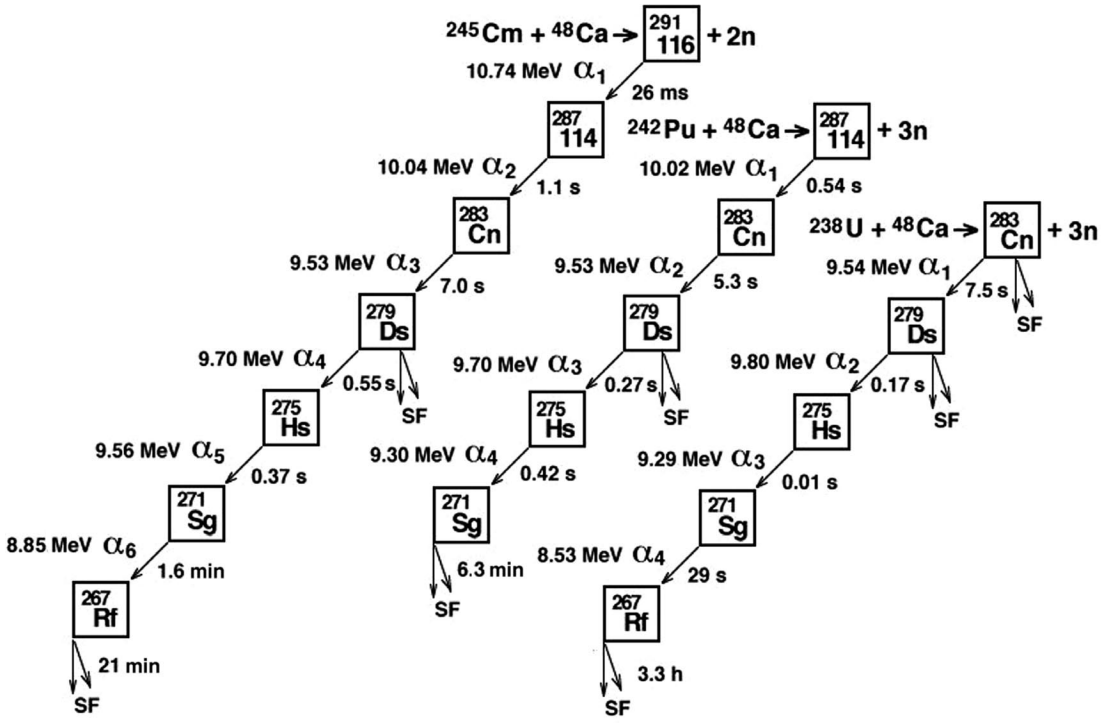


**Fig. 1** A summary of α-particle decay chains observed by Dubna [29–31] and GSI [32] collaborations illustrating the matched characteristics of $^{283}$Cn attained through three otherwise independent entrance bombardment plus α-decay combinations. The compound nucleus excitation energies ranged between 30 and 40 MeV.

(even A) $^{238}$U, $^{242}$Pu, and $^{244}$Pu, and (odd A) $^{245}$Cm targets with combined atomic numbers of 112, 114, and 116, respectively, that persuasively support the assignment of $^{283}$Cn. The latter nuclide then qualifies to serve as a link for heavier decay precursors. A summary of the cross-bombardments funneling through $^{283}$Cn is illustrated in Fig. 1.

The JWP recognizes that identification of this $Z = 112$ isotope supports the physicochemical properties observed by Eichler et al. [17], notably absorption on a gold surface, as being that due to (semi-)metallic behavior. Comparisons to relativistic predictions for element 112 are particularly useful in achieving confident theoretical results. However, comparison of element 112's adsorption behavior to that of radon's adsorption behavior as done seems not necessarily informative since a theoretical prediction for the more relevant eka-radon has not appeared.

## *Z* = 114

### *114; 01 The collaboration of Oganessian et al. [21]*

In 1999, this collaboration found one event in the $^{48}$Ca + $^{242}$Pu fusion assigned to a $^{287}$114 alpha of energy 10.3 MeV and lifetime 1.3 s, which was followed by a spontaneous fission assigned to $^{283}$Cn following a 9 min delay.

JWP ASSESSMENT: The one event and inconclusive identification of the now-known nuclide $^{283}$Cn is not adequate evidence for the discovery of $Z = 114$.

***114;** 02 The collaboration of Oganessian et al. [24]*

Two events were observed by the Oganessian et al. collaboration [24] in the fusion of $^{48}$Ca + $^{244}$Pu assigned to $^{288}$114 decaying by 9.8 MeV alphas to $^{284}$Cn, whose 9.2 MeV α-decays led to the spontaneous fission assigned to $^{280}$Ds. (Subsequently, these chains were reassigned to originate from $^{289}$114 [28].)

***114;** 03 The collaborations of Oganessian et al. [26,27]*

This collaboration used the $^{48}$Ca + $^{248}$Cm fusion initially reported to produce $^{292}$116 for three events assigned to pass through $^{288}$114, which decayed with a 9.8 MeV α-particle emission, followed by a 9.1 MeV α-decay assigned to $^{284}$Cn and then a spontaneous fission. These nuclei were reassigned to $^{293}$116, $^{289}$114, $^{285}$Cn, and $^{281}$Ds in reanalysis [29]. The lifetimes were also in good agreement with the above two events report [24].

JWP ASSESSMENT: Good reproducibility for a total five events is supportive but not sufficient evidence for discovery because the decay chains do not connect to known species and terminate in very non-specific spontaneous fission.

***114;** 04 The collaboration of Oganessian et al. [28]*

This collaboration investigated the fusion $^{48}$Ca + $^{244}$Pu and observed a 1.5 s α-decay with energy 10.0 MeV, assigned to $^{287}$114, followed 5 s later by a 9.5 MeV α-particle assigned to daughter $^{283}$Cn, in partial agreement with the 1999 work [18]. In the same study, fusion was reported to produce three α-decay chains, all commencing with $^{289}$114 and cascading through $^{285}$Cn and $^{281}$Ds where spontaneous fission terminated the sequence in agreement with revised interpretation of the data [24–27].

***114;** 05 The collaboration of Oganessian et al. [30]*

This collaboration observed 13 events in studying the fusion $^{48}$Ca + $^{242}$Pu, commencing with well-reproduced 10.0 MeV α-decay with average lifetime of 0.7 s, then feeding a 9.5 MeV α-decay with an average lifetime of 6 s. These were assigned as $^{287}$114 and $^{283}$Cn, respectively. For the latter, 12 events subsequently continued with spontaneous fission and an average lifetime of 0.3 s. These results are in agreement with the previous study [29]. In the same fusion study, nine events were observed that originated with $^{286}$114. Four of these decayed by 10.2 MeV α-particle emission with good reproducibility, and the remaining five events decayed by spontaneous fission.

***114;** 06 The collaboration of Oganessian et al. [31]*

Fusion of $^{48}$Ca with $^{245}$Cm, reported by the Oganessian et al. collaboration [31], produced α-decay chains assigned to begin with $^{291}$116, passing through $^{287}$114 which emitted 10.0 MeV α-particles in 1 s leading to $^{283}$Cn which, in turn, decayed in two of the events by α-particle emission to $^{279}$Ds, one of which underwent three subsequent α-particle decays terminating allegedly at $^{267}$Rf, while the other fissioned spontaneously. The investigation also included fusion with a $^{249}$Cf target. Three chains were produced, each commencing with 11.7 MeV α-decay by presumed $^{294}118 \rightarrow {}^{290}116$. All three of these events emitted 10.8 MeV α-particles producing $^{286}$114, two of which terminated by spontaneous fission. The third event emitted a 10.2 MeV α-particle and then terminated the sequence by spontaneous fission, presumably of $^{282}$Cn, in 3 ms. In the fusion of $^{48}$Ca + $^{245}$Cm directly to $^{290}$116, five events of 10.2 MeV α-decay in 7 ms from $^{286}$114 followed, terminating subsequently in spontaneous fission.

***114;** 07 The review of Oganessian [33]*

This review reported that the fusion of $^{48}$Ca with $^{248}$Cm produced one three-α-decay chain sequence beginning with $^{292}$116 (10.7 MeV, 26 ms) followed by $^{288}$114 (9.9 MeV, 1.2 s) and terminating at $^{284}$Cn by spontaneous fission in 0.1 s.

JWP ASSESSMENT: The Dubna-Livermore collaborations [28,30,31] all have produced concordant observations of $^{287}$114. In 16 of the events found involving cross-bombardments of $^{48}$Ca with both (even A) $^{242}$Pu and (odd A) $^{245}$Cm, the intermediate $^{283}$Cn was observed with decay characteristics in agreement with those that the JWP has acknowledged establish that nuclide as a "known" sys-

tem. The combination of two entry paths followed by identification of the resulting chains passage through a "known" intermediate meets the existing criteria for establishing discovery of element 114 (Fig. 1).

## *Z* = 116

### *116; 01 The collaboration of Oganessian et al. [27]*

As noted above, this collaboration used fusion of $^{48}$Ca with $^{248}$Cm and measured one event of a 10.56 MeV α-particle assigned to $^{292}$116 with a lifetime of 47 ms. The decay chain was followed by a 9.81 MeV alphas in 2.4 s to $^{288}$114 succeeded by a 9.09 MeV alpha in 54 s to $^{284}$Cn and terminating with spontaneous fission assigned to $^{280}$Ds in 7 s, none of these being established nuclides.

### *116; 02 The collaboration of Oganessian et al. [28]*

Two decay chains assigned to $^{291}$116 were found by this collaboration in the $^{48}$Ca + $^{245}$Cm fusion. 10.9 MeV alphas were followed after 9 s by 10.0 MeV alphas assigned to $^{287}$114 with lifetime 1.6 s to $^{283}$Cn, which decayed in 10 s by emission of 9.5 MeV alphas terminating by spontaneous fission in 0.5 s from $^{279}$Ds. The $^{283}$Cn intermediates are in very good agreement with the accepted behavior of that isotope.

### *116; 03 The collaboration of Oganessian et al. [30]*

This collaboration repeated their earlier study of $^{48}$Ca + $^{245}$Cm fusion and reported six more α-decay events of energy 10.66 ± 0.07 MeV and lifetime 18 ms assigned to $^{292}$116 in good agreement with the 2001 measurement [27], but no further details were published.

### *116; 04 The collaboration of Oganessian et al. [31]*

Oganessian and collaborators investigated the fusion of $^{48}$Ca with two different actinide [actinoid] target isotopes [31]. With $^{245}$Cm, production of six events assigned to $^{290}$116 with α-particle emission of energy 10.9 MeV and lifetime of 10 ms continued in five cases to $^{286}$114. The latter decayed with an α-energy of 10.1 MeV and lifetime 0.1 s, followed in four events by spontaneous fission of $^{282}$Cn in 2 ms. These are all unestablished intermediate nuclides. Also from this fusion combination, one event commencing with $^{291}$116 was reported with a 10.76 MeV alpha and lifetime of 61 ms leading to a 10.0 MeV α-decay of lifetime 9 ms assigned to $^{287}$114 whose product $^{283}$Cn then decayed in 13 s with a 9.6 MeV alpha and then was followed through three more successive α-decays, terminating in spontaneous fission by $^{267}$Rf. The latter part of the decay chain, commencing with the $^{283}$Cn nuclide through $^{267}$Rf, is in very good agreement with the study of $^{48}$Ca + $^{238}$U fusion at Dubna [30].

### *116; 05 The collaboration in Oganessian et al. [33]*

Fusion of $^{48}$Ca with $^{248}$Cf [33] evidenced one chain commencing with $^{292}$116, in which a 10.7 MeV α-decay after 26 ms led to $^{288}$114 which decayed by 9.9 MeV α-emission in 1.2 s to $^{284}$Cn where the sequence terminated by spontaneous fission in 0.1 s. No link to known isotopes is established, and the decay of $^{284}$Cn contrasts with that initially claimed in Dubna's previous study [27].

JWP ASSESSMENT: The 2004 and 2006 Oganessian Dubna-Livermore collaborations [28,31] observe a total of three chains assigned to $^{291}$116 produced in the $^{48}$Ca + $^{245}$Cm fusion, all noted with very good reproducibility to pass via the $^{283}$Cn nuclide, which serves as an established link to identify the atomic number of the members of the decay sequence with confidence (Fig. 1).

## *Z* = 118

### *118; 01 The 2006 collaboration of Oganessian et al. [31]*

This collaboration observed three concordant events from the fusion of $^{48}$Ca with $^{249}$Cf reported to produce $^{294}$118. The product underwent decay with α-particle energy 11.7 MeV in 1.3 ms to $^{290}$116 which, in all events, decayed with α-energy 10.7 MeV in 14 ms to $^{286}$114. Two chains of the latter isotope ter-

minate by spontaneous fission, and the third event emitted a 10.2 MeV α-particle with an average lifetime of 0.15 s. The remaining event terminated by spontaneous fission of $^{282}$Cn in 3 ms.

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.

## COMMENTS

In the discovery profiles, the recognition of conflicting results is not meant to imply experimental error since the likely prevalence of isomeric states among the superheavy nuclides could easily be responsible for the varied observations.

Both the TWG and the JWP recognized that there will be situations in which an early paper did not, at the time, convey conviction of discovery, but that later investigations revealed to have been correct. The existence of the element in question is then, as definitely as practical, established by subsequent work following the lead of the early paper (as was the case here). As has been noted in previous reports, overlap with the prior results or fully characterizing the identity of a descendent in a chain are among the types of co-participation that would need to be carefully taken into account. It would clearly be wrong to assign absolute priority to that early paper. An appropriate consideration of its importance to future decision motivated by new results would bear this in mind.

## SUMMARY OF JWP CONCLUSIONS

The IUPAC/IUPAP JWP performed a critical review of the various claims to discovery of the transcopernicium elements $Z = 113$, 114, 115, 116, and 118. Evidence in the cases of elements $Z = 113$, 115, and 118 have not met the criteria for discovery. For the elements $Z = 114$ and 116, the establishment of the identity of the isotope $^{283}$Cn by a large number of decaying chains, originating from a variety of production pathways essentially triangulating its A,Z character enables that nuclide's use in unequivocally recognizing higher-$Z$ isotopes that are observed to decay through it. The JWP notes that the internal redundancy and extended decay chain sequence for identification of $Z = {}^{287}114$ from $^{48}$Ca + $^{242}$Pu fusion by the 2004 Dubna-Livermore collaborations [29,30] and recommends that the Dubna-Livermore collaboration be credited with discovery of this new element. In a similar manner, the 2004 collaboration of Oganessian et al. [28] report of the production of $^{291}$116 from the fusion of $^{48}$Ca with $^{245}$Cm is supported by extended decay chains that include, again, $^{283}$Cn and descendants. Although there are only two chains in this cited study, subsequent measurements in 2006 in the same laboratory [31] confirm the results. Furthermore, the precedent of basing discovery on two chains has already been established by the JWP in the case of Rg [6]. The Dubna-Livermore collaboration [28] should be credited with the discovery of the new element with $Z = 116$.

In both the $Z = 114$ and $Z = 116$ recommendations, the JWP is aware that earlier "discovery" reports may be confirmed in the future if the identity of relevant intermediate isotopes is unambiguously confirmed.

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