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Evidence for the possible synthesis of element 110 produced by the ^{59}Co+^{209}Bi reaction

A. Ghiorso,[1] D. Lee,[1] L. P. Somerville,[2] W. Loveland,[3] J. M. Nitschke,[1] W. Ghiorso,[1] G. T. Seaborg,[1] P. Wilmarth,[1] R. Leres,[1] A. Wydler,[1] M. Nurmia,[1] K. Gregorich,[1] K. Czerwinski,[1] R. Gaylord,[1] T. Hamilton,[1] N. J. Hannink,[1] D. C. Hoffman,[1] C. Jarzynski,[1] C. Kacher,[1] B. Kadkhodayan,[1] S. Kreek,[1] M. Lane,[1] A. Lyon,[1] M. A. McMahan,[1] M. Neu,[1] T. Sikkeland,[4] W. J. Swiatecki,[1] A. Türler,[5] J. T. Walton,[1] and S. Yashita[6]

[1]*Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720*

[2]*Lawrence Berkeley Laboratory, Berkeley, California 94720*
and University of Lanzhou, Lanzhou, Gansu Province, People's Republic of China

[3]*Department of Chemistry, Oregon State University, Corvallis, Oregon 97331*

[4]*Department of Physics, University of Trondheim, Trondheim, Norway*

[5]*Paul Scherrer Institut, Villigen, Switzerland*

[6]*7-9 Bluebird-Italy, Monte Carlo, MC98000, Monaco*

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An experiment to synthesize element 110 by the ^{59}Co+^{209}Bi reaction has been performed at the SuperHILAC at the Lawrence Berkeley Laboratory. One event with many of the expected characteristics of a successful synthesis of ^{267}110 was observed. This event corresponds to a production cross section of about one picobarn.

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The synthesis of new heavy nuclei and the measurement of their properties frequently allows us to learn new, unexpected features of nuclear structure. For example, in the late 1960s, simple empirical correlations [1] would have predicted that no chemical elements with $Z \geqslant 108$ could be made and studied due to their expected short spontaneous fission half-lives ($\leqslant \mu$s). One of the most striking aspects of the synthesis of elements 107–109 was that the decay of these nuclei was primarily by α decay rather than spontaneous fission and the half-lives were in the millisecond range. These results have been understood in terms of the "shell stabilization" of the ground states of these nuclei. The synthesis and characterization of the isotopes of the next chemical element, element 110, pose challenges to both experimentalists and theorists. This element is predicted to be the last nonsuperheavy element and the isotopes of concern in this report are predicted to have half-lives in the microsecond region. Along with the expected minuscule ($\approx$ pb) production cross sections [2], the expected short lifetimes represent an additional experimental challenge. Previous attempts to produce and detect element 110 nuclei [3,4] via the ^{64}Ni + ^{208}Pb and ^{40}Ar + ^{235}U reactions have been unsuccessful, with cross section limits of $\approx$ 10 pb.

In 1991 we performed an experiment to attempt the synthesis of element 110 via the ^{59}Co+^{209}Bi reaction. In this letter we describe the essence of that experiment and present our evidence for the possible observation of one atom of element 110. A more complete account will be published later. A preliminary account of this work has been presented previously [5]. Very recently, it has been reported that a different isotope of element 110 was synthesized using the ^{62}Ni + ^{208}Pb reaction [6].

To understand our result, one needs to take into account the predicted decay properties of the relevant nuclides made in the chosen reaction. That reaction, ^{209}Bi(^{59}Co,n)^{267}110, was selected simply because of the ready availability of the target and projectile nuclei. The nuclide ^{267}110 is predicted to decay primarily by α-particle emission with an α/SF ratio of $\approx 10^5$ [7]. The predicted value [8] of Q_α is 11.7 MeV, resulting in a maximum α-particle energy of 11.5 MeV. The systematics of α decay [9] would predict an α half-life of ≈ 18 μs for ^{267}110. The predicted α-decay energies and decay half-lives of the other relevant isotopes of element 110 are Q_α= 11.6, 11.9, and 12.0 MeV and $t_{1/2}$= 16, 5, and 6 μs for ^{268}110, ^{266}110, and ^{265}110, respectively. Thus, these products are expected to have half-lives that are 2–3 orders of magnitude shorter than that measured for ^{266}Mt (element 109, meitnerium). The daughter of ^{267}110 is the unknown nuclide ^{263}Hs (element 108, hassium) and is predicted to have Q_α= 11.0 MeV (E_α=10.8 MeV) with a $t_{1/2}$=170 μs. The granddaughter of ^{267}110 is ^{259}Sg (element 106, seaborgium), known [10] to decay by α emission {E_α=9.62(78%), 9.36(11%), and 9.03(11%) MeV} with $t_{1/2}\approx 0.5$ s. It is probable that ^{259}Sg also decays, in part, by electron capture (EC) forming ^{259}Ha since significant (10–35%) EC branches are suggested from semiempirical compilations of EC lifetimes [11] and have been observed for *all* of the other known nuclei with 153 neutrons above β-stable ^{251}Cf, namely ^{252}Es, ^{253}Fm, ^{254}Md, ^{255}No, ^{256}Lr, ^{257}Rf, and ^{258}Ha. The nucleus ^{259}Ha is unknown and is expected to decay by α-particle emission (E_α predicted to be 9.0 MeV, $t_{1/2}\approx 1$ s) leading to known ^{255}Lr {E_α=8.43(40%), 8.37(60%), $t_{1/2}$=22 s}. The α decay of ^{255}Lr leads to unobservable products decaying by EC to long-lived ^{251}Cf as shown in Fig. 1.

The reaction ^{209}Bi(^{59}Co,n)^{267}110 is calculated to have a Q value of -215 MeV and the Coulomb barrier is estimated to be about 300 MeV in the laboratory system. Laboratory projectile energies of 290–310 MeV thus produce excitation energies of the completely fused species of 11–27 MeV. The choice of the optimum projectile energy is difficult as one

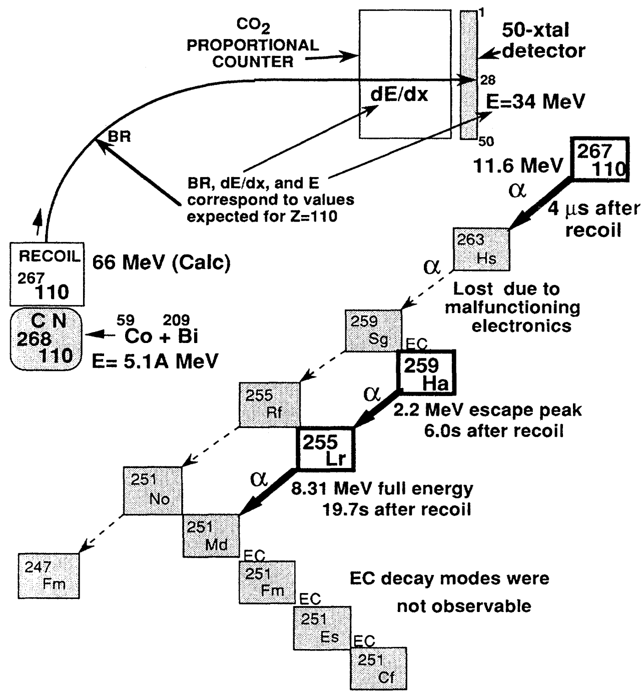

FIG. 1. Proposed scenario for the element-110 event. The highlighted boxes indicate the observed section of the postulated α-decay chain.

balances the probability of fusion of the colliding nuclei vs the survival probability against deexcitation by fission. Although estimates of fusion probabilities and deexcitation of the anticipated product nuclei are possible [12] by the use of phenomenological models, we chose a purely empirical approach for deciding on the optimum projectile energies. Based upon the available systematics [13] of excitation functions for "cold fusion" reactions [14], it appears that the peak of the $1n$-excitation functions might be at an excitation energy E^* of $\approx$20 MeV. Given that our 0.5-mg/cm^2 Bi targets produced a spread in the energies of the interacting ^{59}Co projectiles of $\approx$5 MeV [15], our objective was to use a series of projectile energies corresponding to $15 \leqslant E^* \leqslant 25$ MeV with more emphasis given to the highest projectile energies so as to correspond with the excitation energy observed in the successful synthesis of meitnerium.

The experiment was carried out at the Lawrence Berkeley Laboratory SuperHILAC accelerator, using the gas-filled magnetic spectrometer SASSY2 [16], to isolate a possible element-110 recoil and its decay products. This device was a rebuilt version of the previously-described [17] separator SASSY. SASSY2 differed from its predecessor in that: (a) it had a recoil flight path of 2.5 m, rather than 4 m, to decrease recoil scattering and increase recoil transport efficiency, (b) it had a total bending angle of 55°, rather than 22°, to increase discrimination against beam particles and target-like fragments, (c) it had Hall probes for the direct measurement of the magnetic fields, (d) it had a 30-cm long CO_2-filled proportional counter for a dE/dx measurement just before the focal plane, and (e) it had a larger area, position-sensitive focal plane detector system sensitive to α-particle energies >0.5 MeV. The separator operated at a helium pressure of 1 torr and the CO_2 in the dE/dx proportional counter was at the same pressure.

Each set of nine 1.4×9 cm sector targets, nominally 500 μg/cm^2 Bi metal evaporated onto 150–300 μg/cm^2 Al substrates, was mounted on a 30-cm diameter swiftly rotating wheel. The individual thicknesses were monitored continuously during the experiment by α-particle transmission measurements. The 1-cm diam. beam window which separated the gas-filled spectrometer from the beam line was either a double layer of C foils or an Al-C-Al sandwich with thickness varying from 50–250 μg/cm^2. Because of the occasional failure of windows the beam current was limited to <0.25 particle microamperes for much of the experiment. The intensity of the ^{59}Co beam was monitored during the runs by using the separator itself as a Faraday cup. This method was checked twice by calorimeter measurements. The integrated beam fluence was 1.49×10^{18} ions delivered over a period of 41 days. (58% of this time was spent taking data for the ^{59}Co+ ^{209}Bi reaction.)

The energy of the ^{59}Co beam was measured as it entered the SASSY2 separator in three ways: (1) by using the accelerator phase probes, (2) by measuring the magnetic field of the steering magnet in the beam line leading to the separator, and (3) by the use of silicon detectors. The pulse-height defect for these silicon detectors for $\approx$300-MeV ^{59}Co ions was measured in a subsequent experiment at the LBL 88-Inch Cyclotron. The losses of energy in passing through the thin entrance window, the target backing, and half the target thickness were calculated using standard range-energy relationships [15]. These losses were typically 3.2, 3.3, and 2.7 MeV, respectively. To clarify an ambiguous measurement of the energy used in the particular run where we observed the interesting event, we used the stratagem of determining the energy used in that run relative to the others by examining the yields of target-like transfer products made in the bombardments. These relative yields are sensitive indicators of relative bombarding energies and this measurement showed that the energy used in this particular experiment was about 5.1 MeV/nucleon.

In an earlier test run the transmission of the SASSY2 spectrometer was measured to be 76±8% for the Ac evaporation residues produced in the reaction of 232-MeV ^{51}V with ^{nat}Dy. Following this measurement, a source of ^{249}Cf α particles was used to adjust the spectrometer to improve its transmission and the realigned spectrometer was then found to have an angular acceptance of ±50 mrad in both the horizontal and vertical directions. (An angular acceptance of ±50 mrad implies a transmission of 96–98% for the evaporation residues in this experiment.)

The focal plane detector system was a linear array of five adjacent Si wafers, with each wafer having ten detector strips on it that were 3-mm wide and 28-mm high. Each detector strip was position-sensitive in the 28-mm direction. The depletion depth of the detectors was 100 μm and the average implantation depth of a compound nucleus recoil was 8 μm. The efficiency for detecting a full-energy α-particle signal after recoil implantation was calculated to be 57% in any one detector; the overall average efficiency for detecting any α particle emitted by an implanted recoil with E>0.5 MeV was calculated to be 94%. The detectors had been used previously for a long period of time with a consequent degrada-

TABLE I. Summary of observations of unusual event in detector 28 in run RA1017.

Time of occurrence (s)	Event
0	recoil implantation - deposit of 17.4 MeV
26.224404	recoil implantation - deposit of 34 MeV
26.224408	11.6 MeV α particle
26.373926	8.1 MeV α particle
32.191121	2.2 MeV α particle
45.944494	8.3 MeV α particle
1007.706179	no full energy, heavy element decay signals observed since 8.3 MeV α particle

Type of event	Background rate s^{-1} [a]
Recoils ($E_{rec} \geqslant 15$ MeV)	4.7×10^{-3}
Alpha ($E_\alpha \geqslant 10$ MeV)	1.7×10^{-3}
Alpha ($7.8 \leqslant E_\alpha \leqslant 8.5$ MeV)	1.7×10^{-3}
Alpha ($2.0 \leqslant E_\alpha \leqslant 2.4$ MeV)	4.3×10^{-2}

[a]Duration of run RA1017=2334.3 s.

tion in resolution in energy and position, the former to about 200 keV and the latter to 2 mm, both expressed as FWHM. The signals from the dE/dx detector (which was in front of the focal plane array) were used to identify recoil implantation and fission events, and by their absence, α-particle events.

One unique sequence of correlated signals (in the entire 41 day experiment) was observed at a projectile energy of 5.1 MeV/nucleon (Table I). The sequence began with an implantation in focal plane detector 28 of a recoil depositing 17.4 MeV. About 26 s later, at a site 1.4 mm away from the first recoil implantation, a second recoil atom was implanted, depositing 34 MeV. Four microseconds after the second implantation, an 11.6 MeV α particle was observed at the second implantation site. (The actual recorded pulse height corresponded to 10.8 MeV, but a correction of 0.8 MeV for partial pulse height summing effects was added to this energy. The magnitude of this correction was determined in postrun tests of the electronics.) Approximately 150 ms after the occurrence of the 11.6 MeV α particle, an 8.1 MeV α particle was detected. Then, approximately 6 s after the second recoil implantation, a 2.2 MeV α particle was detected followed by an 8.3 MeV α particle 19.7 s after the second implantation. Following this 8.3 MeV event, no signals corresponding to subsequent heavy element decay α particles ($6 \leqslant E_\alpha \leqslant 8$ MeV) at this site were observed during the duration of run RA1017 (950 s). The positions of all these signals were the same within the limited ($\pm$ 2 mm/28 mm) position resolution of detector 28. Both the 2.2 and 8.3 MeV α particles were detected during the "beam-on" time (30% duty cycle; 8.3 ms on, 19.4 ms off) while the 8.1 MeV α particle was detected during a "beam-off" period. Table 1 also contains the measured singles rates for various types of events in detector 28 during this run.

What are the possible explanations of these unusual events? The counting rates shown in Table I quickly convince one that all these six signals could not have arisen from chance correlations only. There must have been one or more true correlations that occurred. Two very different scenarios have been put forth as the most likely explanations of these data. Scenario A asserts that the first implantation corresponds to the implantation of $^{212}Po^m$($t_{1/2}$=45.1 s, E_α=11.6 MeV) followed by its decay 26 s later by the emission of an 11.6 MeV α particle. In this scenario, the second implantation is that of ^{213}Rn ($t_{1/2}$=25.0 ms, E_α=8.1 MeV) followed by its decay 150 ms later by the emission of an 8.1 MeV α particle. The correlations with the 2.2 and 8.3 MeV α particles are assigned to chance correlations. Scenario B, which we favor (Fig. 1), asserts that the first implantation was that of an unknown activity which resulted in its decay 26.37 s later by the emission of an 8.1 MeV α particle. The second implantation, we assert, was most probably an atom of $^{267}110$, followed 4 μs later by its decay by the emission of an 11.6 MeV α particle. [The possibility that the implanted recoil was $^{267}109$ (the result of proton emission by the completely fused system) can be ruled out due to the low expected value of Γ_p/Γ_n and the fact that the expected α-particle energy for the decay of $^{267}109$ would be 11.1 MeV [8].] The next decay in the chain, that of ^{263}Hs, was missed due to a malfunctioning transient recorder that created an effective electronic deadtime of 0.280 ms. We suggest that the next member of the chain, ^{259}Sg, undergoes undetected EC decay to ^{259}Ha. The decay of ^{259}Ha is manifested by the detection of a 2.2 MeV α particle, representing a partial escape of the ^{259}Ha α particle. Finally 22 s ^{255}Lr decays 19.7 s after implantation with the emission of an 8.3 MeV α particle. The period of 950 s with no signals being recorded is consistent with the occurrence of EC decays to long-lived ^{251}Cf. This single event would correspond to a production cross section of about one picobarn for this reaction if all beam energies were deemed to be equally likely to produce it.

What are the strengths and weaknesses of these two scenarios? Both scenarios postulate two recoils implanting within 26 s and within 2 mm of each other. The singles rates would indicate that, on the average, about 0.2 such dual implants should have occurred within 26 s in this run if the recoils were uniformly distributed over the detector area. In both scenarios, at least one of these recoils has $A \simeq 213$. Implantation of such a recoil in this region of the focal plane where one expects $^{267}110$ recoils is a rare event resulting from multiple scattering within the separator [17,16]. Scenario A postulates two straightforward, known implantation and decay sequences. It naturally accounts for the occurrence of both an in-beam and an out-of-beam decay. But it must assign both the 2.2 and 8.3 MeV correlations to chance. [One expects 1.8×10^{-4} such chance coincidences in this run occurring at intervals of 6 and 20 s, or, more conservatively, 5.9×10^{-4} such chance coincidences occurring at intervals of 6 and 66 s ($3 \times {}^{255}\text{Lr}\ t_{1/2}$).] This is a problem along with the high recoil energy seen in the second implantation [the observed 34 MeV is close to that expected (40 MeV) for an element 110 recoil]. [The calculated initial recoil energy for a CN recoil is 66 MeV (at the center of the target), with a 15 MeV energy loss in traversing the spectrometer and an estimated pulse height defect of 11 MeV. The pulse height defect was estimated based on measurements of the pulse height defect for low energy Bi ions in a subsequent experiment.] In addition, scenario A requires the occurrence of one decay, that of ^{213}Rn, approximately 6 half-lives after implantation.

What about scenario B, the possible synthesis of element 110? It is a complete scenario accounting for all the observed correlated signals (and the lack of same where relevant). (The number of spatial correlations between a complete fusion recoil, followed 4 μs later by an 11.6 MeV α particle, with the occurrence of a 2.2 MeV and a 8.3 MeV α particle some 6 and 20 s later by chance is such that one would expect 10^{-12} events of this type in this run. More conservatively, the number of spatial correlations between a complete fusion recoil followed within 280 μs by an 11.6 MeV α particle with the occurrence of a 2.2 MeV and a 8.3 MeV α particle some 6 and 66 s later by chance is 4.4×10^{-10} for the run RA1017 and 3.9×10^{-7} for the entire 2×10^6 s experiment.) Its principal drawback is the troubling need to postulate the occurrence of several unproven or untoward events. These occurrences are: (a) the failure to observe the daughter decay due to equipment failure, (b) the postulation of a possible, but unknown (10–35% probability) EC branch in the decay chain, (c) the observation of two decays (2.2 and 8.3 MeV) "in-beam" (probability 0.3^2), and (d) the correlation with an unknown recoil implantation and decay. While there is no way to assign a meaningful probability to (a) above, we can comment further on (d). We have analyzed our data for other such rogue implants in detector 28, in other detectors and in other runs. Our preliminary analysis indicates the occurrence of several events in which an 8.1 MeV α-particle signal was preceded by a recoil implant several seconds earlier. An analysis of the correlation times indicates the parent recoil has a half-life of ~35 s. One might associate these events with the implantation of ^{213}Fr ($t_{1/2}$=34.6 s) followed by EC decay of ^{213}Fr to ^{213}Rn ($t_{1/2}$=25 ms) followed by the α decay of ^{213}Rn (E_α=8.1 MeV). However, since the EC-branching ratio of ^{213}Fr is known to be only 0.9%, it is unlikely that one would observe the α decay of the daughter, ^{213} Rn, following electron capture rather than that of its mother, ^{213}Fr. There is little or no evidence for correlated events in any run in which an implanted recoil decays by the emission of a 6.77 MeV α particle as one would expect for the principal decay mode of ^{213}Fr. This situation leaves us with the problem of postulating the implantation of an unknown precursor of the 8.1 MeV α emitter.

In summary, let us review the evidence for the association of the observed event with the formation of $^{267}110$. The $B\rho$ and dE/dx of the implanted recoil are consistent with values expected for element 110. The recoil energy strongly indicates a CN recoil, rather than a transfer product. The 11.6 MeV α particle indicates either Z=110 or $^{212}\text{Po}^m$, the only known α emitter with such a high decay energy. This scenario (B) accounts for all the observed signals. It is orders of magnitude more probable than any postulated competing scenario (such as scenario A). The association of this event with the possible formation of element 110 appears to be the simplest explanation for our observations. Unfortunately, the SuperHILAC has been shut down and the SASSY2 separator has been dismantled, so that it is impossible for us to repeat the experiment in the very near future. In due time we hope to confirm our findings with a new separator at the LBL 88-Inch Cyclotron. We chose to report this information at this stage in the hope that it will be of value to others in the field.

We wish to acknowledge the outstanding performance of the SuperHILAC and its operations staff headed by H. Syversrud who produced and delivered ^{59}Co beams of as much as 1 pμa over this long period. We wish to thank K. Moody for helpful discussions regarding EC lifetimes. One of us (T.S.) would like to acknowledge the Norwegian Research Council for financial support. This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and Grant No. DE-FG06-88ER40402.

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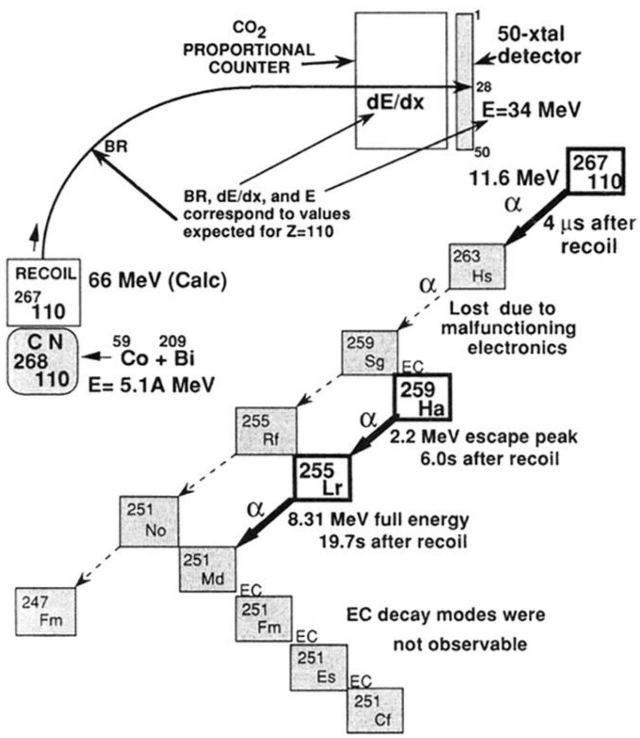

FIG. 1. Proposed scenario for the element-110 event. The highlighted boxes indicate the observed section of the postulated α-decay chain.