New Isotope ^{263}Hs

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ABSTRACT

A new isotope of Hs was produced in the reaction ^{208}Pb(^{56}Fe, *n*)^{263}Hs at the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory. Six genetically correlated nuclear decay chains have been observed and assigned to the new isotope ^{263}Hs. The measured cross section was $21^{+13}_{-8.4}$ pb at 276.4 MeV lab-frame center-of-target beam energy. ^{263}Hs decays with a half-life of $0.74^{+0.48}_{-0.21}$ ms by α-decay and the measured α-particle energies are 10.57 ± 0.06, 10.72 ± 0.06, and 10.89 ± 0.06 MeV. The experimental cross section is compared to a theoretical prediction based on the *Fusion by Diffusion* model [W. J. Świątecki *et al*., Phys. Rev. C **71**, 014602 (2005)].

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Compound nucleus - evaporation reactions between projectiles ranging from ^{48}Ca to ^{70}Zn and shell-stabilized ^{208}Pb and ^{209}Bi targets allow compound nuclei to be created at excitation energies as low as 12 MeV. These reactions, generally referred to as “cold fusion” reactions, have been used in the discovery of elements 107-111 [1, 2], and for the

production of elements 112 and 113 [3-5]. In 1984, element 108 (Hs) was discovered at the Gesellschaft für Schwerionenforschung mbH (GSI) in Darmstadt, Germany, via the ^{208}Pb(^{58}Fe, *n*)^{265}Hs reaction [6]. In our studies we used a similar reaction, ^{208}Pb(^{56}Fe, *n*)^{263}Hs, to search for the neutron deficient ^{263}Hs.

Potential production of one atom of ^{263}Hs as the α-decay daughter of ^{267}Ds was reported in a tentative ^{267}Ds decay chain [7, 8], but ^{263}Hs decay was not recorded due to malfunctioning electronics. It is noteworthy that the Ref. [7] authors' interpretation of the hypothetical ^{267}Ds chain is not supported by new data, as ^{259}Sg has been observed to exclusively decay by α-decay but never by EC-decay [9, 10] and the upper limit for the EC decay mode of ^{259}Sg is < 13% [9]. Here we report the first observation of ^{263}Hs.

The experiments were carried out at the Lawrence Berkeley National Laboratory (LBNL) 88-Inch Cyclotron. The LBNL Advanced Electron Cyclotron Resonance source (AECR-U) [11] was used to produce a $^{56}Fe^{+13}$ ion beam, which was accelerated by the cyclotron to an energy of 280 MeV. First the beam passed through a 45 μg/cm^2 carbon window that separates the beamline vacuum from the helium gas at a pressure of 66 Pa inside the Berkeley Gas-filled Separator (BGS) [12-14]. The beam then entered the 250 μg/cm^2 thick metallic ^{208}Pb (98.4% ^{208}Pb, 1.1% ^{207}Pb, and 0.5% ^{206}Pb) targets, which were evaporated on 40 μg/cm^2 carbon backings and covered by a 5 μg/cm^2 carbon layer. The lab-frame beam energy at the center of the target was 276.4 MeV [15, 16]. The energy loss in the target was approximately 2.8 MeV [15, 16]. The compound nucleus excitation energy, E*, corresponding to the center-of-target beam energy was 15.2 MeV. The excitation energy was calculated by using experimental masses [17] for the target and projectile, and a theoretical mass [18, 19] for the compound nucleus.

The systematic error in the absolute cyclotron beam energy was 1%. The beam intensities ranged from 0.15 - 0.52 particle-μA or (0.93 - 3.2) · 10^{12} particles/s. The integrated beam dose was 8.7 · 10^{17} ions. The recoiling evaporation residues (EVR) were separated in the BGS from the unwanted reaction products based on their differing magnetic rigidities in helium gas. The magnetic rigidities were estimated by using a semi-empirical formula [13]. The BGS efficiency, *eff*, the fraction of all produced Hs EVRs that are implanted into the focal plane Si-strip detector, has been estimated by means of a Monte Carlo simulation of EVR trajectories in the BGS [12], which resulted in *eff* = 0.76±0.08.

The detection setup was identical to the one used for ^{208}Pb(^{50}Ti, *n*)^{257}Rf experiment with the thin lead targets in Ref. [20], where it is described in detail. Before implanting into the Si-strip focal plane detector array, the EVRs passed through a multi-wire proportional counter, MWPC, located upstream from the focal plane detector. The MWPC allowed for discrimination between implantation events and radioactive decay events in the Si-strip focal plane detector. The focal plane consisted of 48 silicon strips which provided a horizontal resolution. The vertical position resolution within a single strip depends on the energy E deposited in the focal plane detector by an α-particle or an EVR and can be approximated by $\sigma_y(E) = 2800$ keV mm/E. To improve the detection efficiency for α-particles or fission fragments emitted from the species implanted in the focal plane detector, additional silicon cards were mounted perpendicular to the focal plane detector in a five-sided box configuration. When partial energies of an α-particle or of fission fragments were detected both in the focal plane detector as well as in the non-position-sensitive “upstream detector”, the total energy is the sum of focal plane and

upstream energy. We refer to these events as “reconstructed events”. A “punch-through” detector was mounted directly behind the focal plane detector. Signals from the punch-through detector were typically due to light, low-ionizing particles and were used to veto any coincident signal in the focal plane detector.

The detector was calibrated by an external 4-point alpha calibration source containing ^{148}Gd, ^{239}Pu, ^{241}Am, and ^{244}Cm. The calibration was performed before and after the experiment to insure that no energy shifts had occurred during the experiment. The energy resolution of α-particles emitted from nuclei implanted in the focal plane detector was 55 keV full-width at half-maximum (FWHM). To minimize the contribution from randomly correlated unrelated events, a fast beam-shutoff was employed whenever an “EVR-like event” (15 < E (MeV) < 35, coincident with the MWPC, anti-coincident with the punch-through and upstream detector signals) was detected and followed within 10 ms by a “Hs-like event” (8.0 < E (MeV) < 12.0, focal plane only, or reconstructed from focal plane + upstream detectors, no MWPC signal, no punch-through signal). The beam was switched off for 180 s, allowing us to observe possible decays of seaborgium, rutherfordium, nobelium or fermium daughters in a low background environment. The rate of “EVR-like events” was 0.53 Hz. To allow for an unambiguous assignment, we only considered chains in which an EVR was followed by at least two full energy α-particles in the chain or a full energy α-particle and a spontaneous fission (SF). ^{263}Hs was identified by observing an “EVR-like event” followed by a “^{263}Hs-like event” within 10 ms, and then by i) at least two of the ^{259}Sg, ^{255}Rf, and ^{251}No daughters (7.5 < E (MeV) < 9.5, no MWPC signal, no punch through signal) within 15 s, or ii) SF (E > 90 MeV), within 10 s. The rate of “^{263}Hs -like” events

was 0.0015 Hz and the rate of α-particles in the beam-off period was 0.013 Hz. The rate of the "SF-like" events was $6.3 \cdot 10^{-6}$ Hz.

The observed decay chains of ^{263}Hs are shown in Figure 1a along with the average properties of the decay chain members in Figure 1b. Besides full energy α-particles and SF, some of the chains contained other types of events: (1) missing α-particle events in which an *α*-particle is not detected and is missing from the chain and (2) escape events in which an *α*-particle "escapes" from the surface of the focal plane detector and leaves only a partial signal in it (typically 0.5–5 MeV) and does not hit the upstream detector. The two escape events that we ascribe to being members of chains 3 and 5 occurred in the same position (same strip and with the vertical position within ±1.5 mm) as the rest of the respective chain, and their lifetimes are consistent with the half-lives of the isotopes we expected at that position within the chains based on other chain members. In the ^{208}Pb(^{56}Fe, *n*)^{263}Hs experiment a total of six chains were observed, and 0.06 chains containing at least two full energy α-particles are expected as a result of random correlations of unrelated events.

The properties of ^{255}Rf, ^{251}No, and ^{247}Fm are in agreement with those reported in Ref. [21], and those of ^{259}Sg agree with those from [9, 10]. In Figure 1a) the times represent the lifetimes of the nuclei, while in Figure 1b), the times are half-lives of the nuclei. Among the ^{263}Hs decays, all but one had a full energy α-particle registered in the focal plane detector. ^{263}Hs in chain 3 had 361 keV registered in the focal plane, and is classified as an escape event. In chain 5, one of the alpha particles was not registered in the focal plane, and is labeled as "missing". In the same chain, the α-particle energy of

^{247}Fm was deposited in the focal plane and the upstream detector and the total energy is represented as the sum of the two energies.

The measured magnetic rigidity of the EVRs inside the BGS was 2.14 T·m, indicative of an average charge state of 7.6. The measured cross section at 276.4 MeV center-of-target lab-frame energy was $21^{+13}_{-8.4}$ pb. The cross section was calculated based on 6 events and only the statistical contributions to the error are given (84% confidence level). The measured half-life of ^{263}Hs is $0.74^{+0.48}_{-0.21}$ ms. In ^{263}Hs we only observed α-decay, resulting in an upper limit for SF branching (b_{SF}) of 8.4 %. Q_α = 11.06 MeV can be deduced from the ^{263}Hs α-decay energies, assuming that the highest α-particle energy group, 10.89 MeV, is from the ground state to ground state transition. The value is in agreement with most of the theoretical predictions: Muntian *et al*. predict Q_α = 10.86 MeV [22], M□ller *et al.* predict Q_α =10.71 MeV [23], and Myers and Świątecki predict 10.91 MeV [18].

The optimum beam energy and the associated maximum cross section at that energy were calculated with the *Fusion by Diffusion* (FBD) model [24, 25] , developed by Świątecki, Wilczyńska, and Wilczyński. The experimental cross section for the ^{208}Pb(^{56}Fe, *n*)^{263}Hs reaction was $21^{+13}_{-8.4}$ pb at the lab-frame energy of 276.4 MeV, while the FBD predicts the maximum cross section of ~ 20 pb at 275 MeV [26]. Therefore, the FBD prediction is in a good agreement with the experimental results. Because the cross section is measured at only one energy, it is impossible to deduce if 275 MeV is indeed the optimum energy. The theoretical excitation function along with the experimental point is shown in Figure 2.

In conclusion, six chains of ^{263}Hs have been observed in the ^{208}Pb(^{56}Fe, *n*) reaction. We have observed only α-decays of this neutron-deficient isotope of hassium and determined the upper limit for b_{SF} to be 8.4 %. We have observed three α-particle energy groups at 10.57 ± 0.06, 10.72 ± 0.06, and 10.89 ± 0.06 MeV. The half-life of ^{263}Hs is $0.74^{+0.48}_{-0.21}$ ms. With the discovery of this most neutron-deficient known member, the Hs isotopic chain is now approaching the deformed neutron shell N = 152. The measured cross section value for the ^{208}Pb(^{56}Fe, *n*) ^{263}Hs reaction is helpful in gaining a systematic picture of the influence of the difference in projectile neutron number on the cross section, which will be the topic of a forthcoming publication [27]. The experimental cross section agrees remarkably well with the FBD prediction.

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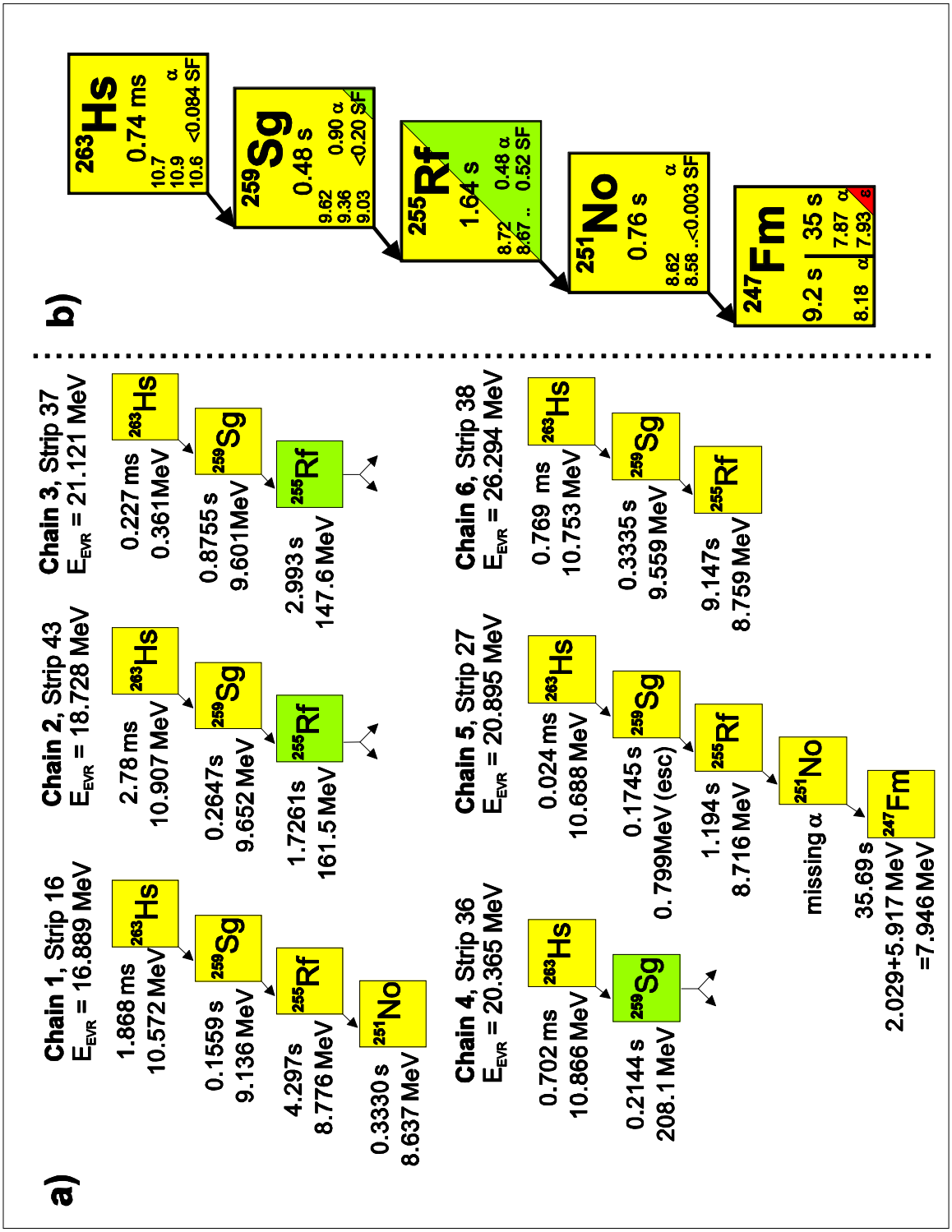
a)
Chain 1, Strip 16
E_EVR = 16.889 MeV
1.868 ms
10.572 MeV
263Hs
0.1559 s
9.136 MeV
259Sg
4.297s
8.776 MeV
255Rf
0.3330 s
8.637 MeV
251No
Chain 2, Strip 43
E_EVR = 18.728 MeV
2.78 ms
10.907 MeV
263Hs
0.2647s
9.652 MeV
259Sg
1.7261s
161.5 MeV
255Rf
Chain 3, Strip 37
E_EVR = 21.121 MeV
0.227 ms
0.361MeV
263Hs
0.8755 s
9.601MeV
259Sg
2.993 s
147.6 MeV
255Rf
Chain 4, Strip 36
E_EVR = 20.365 MeV
0.702 ms
10.866 MeV
263Hs
0.2144 s
208.1 MeV
259Sg
Chain 5, Strip 27
E_EVR = 20.895 MeV
0.024 ms
10.688 MeV
263Hs
0.1745 s
0.799MeV (esc)
259Sg
1.194 s
8.716 MeV
255Rf
missing α
251No
35.69 s
2.029+5.917 MeV
=7.946 MeV
247Fm
Chain 6, Strip 38
E_EVR = 26.294 MeV
0.769 ms
10.753 MeV
263Hs
0.3335 s
9.559 MeV
259Sg
9.147s
8.759 MeV
255Rf
b)
263Hs
0.74 ms
10.7
10.9
10.6
α
<0.084 SF
259Sg
0.48 s
9.62
9.36
9.03
0.90 α
<0.20 SF
255Rf
1.64 s
8.72
8.67 ..
0.48 α
0.52 SF
251No
0.76 s
8.62
8.58 ..<0.003 SF
α
247Fm
9.2 s
35 s
8.18 α
7.87 α
7.93 ε

FIG. 1 (Color online). a) Observed ^{263}Hs decay chains. The times listed represent the measured lifetimes. Energies that are represented as sums are reconstructed events with the focal plane energy being listed first, and the upstream energy listed second. b) The decay properties of ^{263}Hs (from this work) and its daughter nuclides (^{255}Rf, ^{251}No, and ^{247}Fm as given in [21] and ^{259}Sg from [9, 10]). The times given are half-lives.

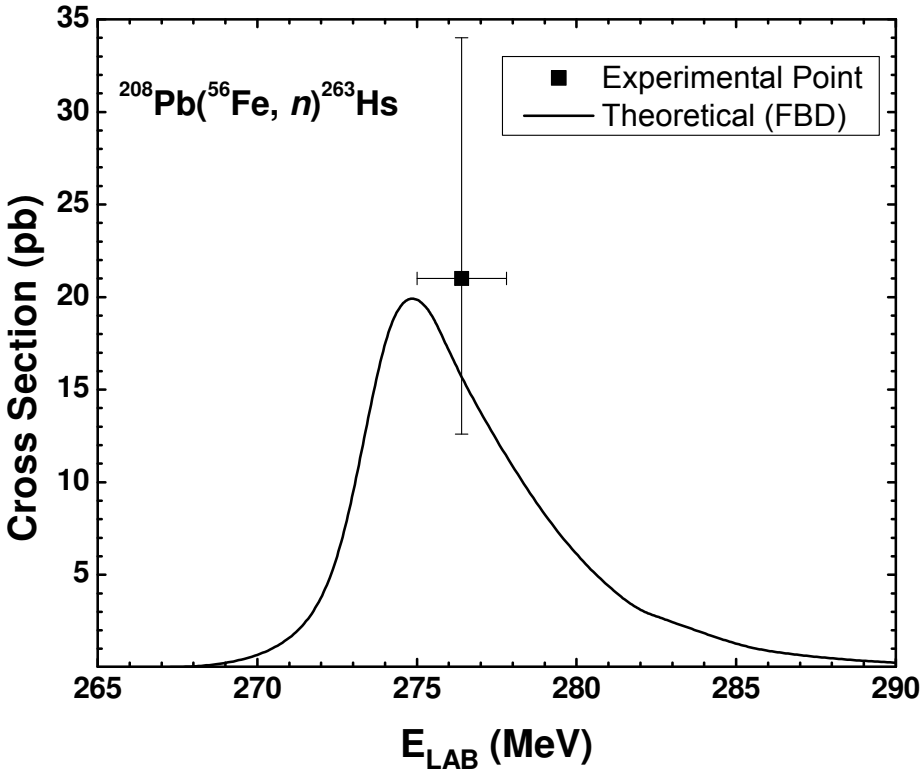

FIG. 2 The theoretical ^{208}Pb(^{56}Fe, *n*)^{263}Hs excitation function according to the *Fusion by Diffusion* model, along with the measured experimental cross section.