Doubly Magic Nucleus $^{270}_{108}Hs_{162}$

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Theoretical calculations predict ^{270}Hs ($Z = 108$, $N = 162$) to be a doubly magic deformed nucleus, decaying mainly by α-particle emission. In this work, based on a rapid chemical isolation of Hs isotopes produced in the ^{26}Mg + ^{248}Cm reaction, we observed 15 genetically linked nuclear decay chains. Four chains were attributed to the new nuclide ^{270}Hs, which decays by α-particle emission with $Q_\alpha = 9.02 \pm 0.03$ MeV to ^{266}Sg which undergoes spontaneous fission with a half-life of 444^{+444}_{-148} ms. A production cross section of about 3 pb was measured for ^{270}Hs. Thus, ^{270}Hs is the first nucleus for which experimental nuclear decay properties have become available for comparison with theoretical predictions of the $N = 162$ shell stability.

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Superheavy elements owe their existence exclusively to nuclear shell effects which stabilize them against spontaneous fission (SF). Theoretical predictions located the center of stability at the hypothetical doubly-magic spherical nucleus with $Z = 114$ and $N = 184$ [1,2]. This picture of an island of relatively long-lived nuclei far from the known quasistable ^{238}U was modified with the inclusion of higher orders of deformation [3–5]. These calculations suggested the ground state shell correction energy of deformed nuclei around $Z = 108$ and $N = 162$ to reach values as large as for ^{298}114. Relatively long partial SF half-lives were calculated for nuclei near ^{270}Hs [6], rendering α-decay the predominant decay mode. Shells at $N = 162$ neutrons and $Z = 108$ protons were predicted by macroscopic-microscopic, as well as self-consistent mean-field (e.g., SLy4) calculations [3–5]. In Fig. 1 calculated α-decay energies (Q_α) of even-even nuclei [7,8] are plotted along with experimentally measured values [9–11]. The increased stability leads to local minima at the $N = 162$ neutron shell and a large difference in Q_α values between Ds and Hs isotones. This is clearly visible in Fig. 1, but so far no experimental α-decay energies are available for $N = 162$ nuclei. The appearance of a region of shell stabilized deformed superheavy nuclei, which extends toward the region of spherical superheavy elements holds the promise of the existence of sufficiently long-lived nuclei for chemical investigations of almost all elements up to $Z = 114$. In recent years the synthesis of a number of superheavy nuclei with $112 \leq Z \leq 118$, exhibiting half-lives as long as few seconds, was reported in ^{48}Ca induced reactions on various actinide targets [12]. Lazarev *et al.* discussed enhanced nuclear stability near $Z = 108$ and $N = 162$ by assigning α-decay to the even-even nuclide ^{266}Sg produced in the reaction ^{248}Cm(^{22}Ne, $4n$) [13]. A large difference between the α-decay energies of ^{273}Ds and ^{269}Hs in the decay chains of ^{277}112 was also seen as an indication for the presence of a $N = 162$ neutron shell

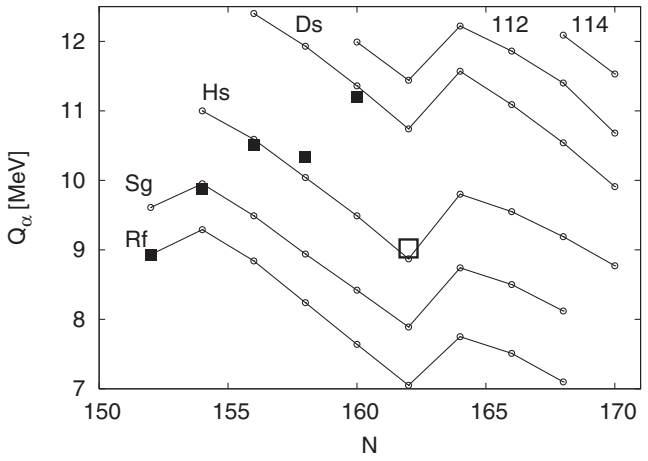

FIG. 1. Comparison of Q_α values from theoretical calculations [7,8] and experimental data [9–11]. The Q_α value obtained in this work for ^{270}Hs is depicted with an open square.

[14]. In this Letter, we report the first synthesis and identification of the even-even nucleus ^{270}Hs and the observation of its α-decay to ^{266}Sg. Contrary to earlier reports [13,15] ^{266}Sg is not decaying by α-particle emission but by SF with a relatively short half-life.

A beam of $^{26}Mg^{5+}$ ions was delivered by the UNILAC at the GSI Darmstadt with two energies, 193 and 185 MeV. Typical beam intensities on target were 0.8 particle μA. Before entering the target material, the beam passed through 19.7 μm thick Be vacuum windows, 6 mm of He-O_2 mixture (10% O_2) and 15.3 μm thick Be backings of the target material. The target consisted of 3 arc shaped segments with average thicknesses of 788 $\mu g/cm^2$, 743 $\mu g/cm^2$ and 244 $\mu g/cm^2$ of Cm (^{248}Cm 95.8%, ^{246}Cm 4.2%). One segment contained 2% in weight of ^{152}Gd (30% enrichment) for the simultaneous production of α-decaying Os isotopes, a chemical analog to Hs. The two beam energies in the targets were 144.0–145.9 MeV and 134.6–136.6 MeV [16] that correspond to the expected cross section maxima for the 5n and 4n evaporation channels, respectively. Beam integrals of 1.46×10^{18} and 2.02×10^{18} $^{26}Mg^{5+}$ ions were accumulated at 145 and 136 MeV, respectively.

A very efficient rapid chemical separation and on-line detection method [17–19] was used for the isolation of Hs. The hot (400 °C) recoil chamber was flushed with 1.5 or 1.8 l/ min gas. Recoil products were thermalized in the gas mixture kept at 1.1 bar and volatile HsO_4 and OsO_4 were formed and passed through a hot quartz wool filter (650 °C). They were transported through an 8-m long Teflon^{TM} capillary (i.d. 2 mm) to the detection system within approximately 2 s. The separation factor from nonvolatile species was $>10^6$.

The detection system consisted of a linear array of 2×32 PIPS detectors in two Invar^{TM} profiles forming a vacuum tight gas channel. The active area of a single detector was (9.3×9.3) mm^2 and the distance between opposite detectors was 0.5 mm. The temperature ranged from +20 °C to −140 °C along the detector array. Detectors were calibrated off-line with ^{219}Rn and its α-decaying products emanating from an ^{227}Ac source. The energy resolution was better than 50 keV (FWHM) under experimental conditions.

Because of the chemical separation, only α-lines originating from $^{172-174}$Os, ^{211}At and ^{219,220}Rn and their daughters were identified. Unfortunately, aerosol particles created by sputtering of the target material were not completely retained by the filter resulting in a background of approximately one SF event every two hours in the whole detector array. Therefore SF-decaying Hs isotopes could not be identified. The area of interest at α-particle energies of 8.0–9.5 MeV contained 145 events in the first 25 detector pairs. 25 of these events were members of correlated decay chains. Background events were attributed mainly to ^{212}Po originating from the in-flight decay of ^{220}Rn.

A decay chain was defined as an α-decay occurring in the energy range from 8.0–9.5 MeV followed within 300 s in the same or a neighboring detector pair (i) by an α-decay in the same energy window or (ii) by a SF. The search procedure was repeated within the chain until no further α-decay was registered. The data analysis revealed 15 correlated decay chains in the first 25 detector pairs—eight at a beam energy of 145 MeV and seven at 136 MeV. All chains are listed in Table I. Because of the α-particle and SF background, pseudocorrelated sequences can be formed with nonzero probability. Based on measured count rates

TABLE I. Correlated decay chains. Given are the number of the chain, the beam energy at which it was observed, energies of individual events (E_1 to E_4), the observed lifetimes of the daughter nuclei (Δt_2-Δt_4), and the assignment of the chain. The detector in which an event was observed is given in parenthesis, "T" stands for "top detector" and "B" for "bottom detector". Energies are given in MeV, fission fragment energies are not corrected for pulse height defect.

No.	E_{beam}	E_1	E_2	Δt_2	E_3	Δt_3	E_4	Δt_4	Assignment
1	145	8.93 (16T)	8.69 (16B)	32.5 s	8.29 (16T)	32.1 s	8.29 (17B)	2.50 s	^{269}Hs
2	145	9.06 (13B)	8.68 (14T)	85.6 s	93 (14T)	4.44 s			^{269}Hs
3	145	9.11 (1B)	8.68 (1B)	2.48 s	67/13 (1T/1B)	7.09 s			^{269}Hs
4	145	8.91 (15B)	8.65 (15B)	6.75 s	29 (15T)	6.69 s			^{269}Hs
5	145	9.03 (18T)	8.60 (18T)	7.70 s	111/26 (18T/19B)	6.42 s			^{269}Hs
6	145	8.92 (19B)	8.72 (19T)	6.82 s	90/101 (19T/19B)	1.29 s			^{269}Hs
7	145	8.35 (22B)	38 (22B)	116 ms					no assignment
8	145	8.85 (14T)	100/74 (14T/13B)	1.62 s					^{270}Hs
9	136	9.08 (15B)	8.71 (15T)	8.70 s	100/74 (15T/16B)	580 ms			^{269}Hs
10	136	9.10 (14T)	80/90 (14T/13B)	96.0 s					^{269}Hs[a]
11	136	8.90 (12T)	89/55 (12T/11B)	49.6 ms					^{270}Hs
12	136	8.92 (5T)	106/82 (5T/5B)	449 ms					^{270}Hs
13	136	8.88 (19T)	96/110 (19T/19B)	444 ms					^{270}Hs
14	136	9.30 (7T)	8.20 (7T)	149 s	89/95 (7T/7B)	12.0 s			^{271}Hs[a]
15	136	8.67 (9T)	117/102 (9T/9B)	306 ms					no assignment

[a]Tentative assignment.

the following number of random sequences can be expected in our experiment: 3×10^{-5} for α-α-α-α, 5×10^{-3} for α-α-SF, and 1 for α-SF.

At a beam energy of 145 MeV mainly production of ^{269}Hs is expected [19,20]. The decay of ^{269}Hs has been observed previously in several different experiments [14,19–22]. In all previously performed experiments ^{269}Hs decayed by α-particle emission followed by α-decay of ^{265}Sg to ^{261}Rf which decayed by SF or by emission of an α-particle ($E_\alpha = 8.5$ MeV, $b_{SF} \sim 40\%$, $T_{1/2} = 4$ s). For ^{261}Rf, a second state is known ($E_\alpha = 8.28$ MeV, $b_{SF} \leq 10\%$, $T_{1/2} = 78$ s) [23,24]. We denote the 78 s state with ^{261a}Rf and the 4 s state with ^{261b}Rf. In [19,20], two decay chains were tentatively assigned to ^{270}Hs based on the previously reported decay properties of ^{266}Sg [13,15] and ^{262}Rf [25]. However, this tentative assignment was not conclusive as the reported ^{270}Hs decay chains consisting of α-α-SF decay sequences were very similar to the ones assigned to ^{269}Hs.

Chains Nos. 1–6 and No. 9 exhibit decay properties similar to those observed in [14,19–22] for the decay of ^{269}Hs. Decay chains Nos. 1–6 were observed at a beam energy of 145 MeV and No. 9 at 136 MeV. The first α-decay of these chains with an energy between 8.91 and 9.11 MeV is attributed to the decay of ^{269}Hs. The energies of the second α-decay, attributed to ^{265}Sg, have a narrow distribution 8.68 ± 0.04 MeV. The α-decay energies and lifetimes, detected in chain No. 1 fit well to the known α-decay energies of ^{261a}Rf and ^{257}No [11].

In chain No. 10, the energy of the α-particle is in agreement with the energies observed in chains Nos. 1–6 and No. 9, but no second correlated α-particle was detected. This can be explained by missing the α-decay of ^{265}Sg. Therefore, this chain is tentatively attributed to ^{269}Hs, but alternatively it may also be of random origin.

Six more α-SF chains were detected, four out of these, No. 8 and Nos. 11–13 exhibit a narrow distribution of α-particle energies with $E_\alpha = 8.89 \pm 0.03$ MeV. They were terminated by SF with an average lifetime of $\sim$0.5 s. This sequence is different from all known decay patterns. As the detection efficiency for an α-particle is 80%, there is a less than 0.1% probability that these observed α-SF chains are incomplete α-α-SF ones, where always the same α-particle was missed. Three out of four chains were detected at the lower beam energy at the expected maximum of the $4n$ evaporation channel. Therefore, we assign these four chains to the decay of the new isotope ^{270}Hs and its daughter ^{266}Sg. From the measured α-particle energy, $Q_\alpha = 9.02 \pm 0.03$ MeV for ^{270}Hs was derived. Several theoretical calculations of Q_α of ^{270}Hs have been performed and most of them are in agreement with our measured data, e.g., $Q_\alpha = 8.69$ MeV [26]; $Q_\alpha = 8.83$ MeV [27]; $Q_\alpha = 8.87$ MeV [7,28], $Q_\alpha = 8.90$ MeV and $Q_\alpha = 9.54$ MeV [29] and $Q_\alpha = 9.13$ MeV [30]. The partial α-decay half-life of ^{266}Sg is predicted as $T_\alpha = 48$ min [27] and $T_\alpha = 4.5$ min [28] while that for SF is predicted as $T_{SF} = 58$ s [6] and $T_{SF} = 100$ μs [31] suggesting SF as the likely decay mode. We are aware that the assignment of our experimental findings is in contradiction to the interpretation of earlier works; ^{266}Sg was reported to decay by α-particle emission with a half-life of a few tens of seconds [13,15,32–34]. An earlier Hs chemistry experiment [19,20] reported indications for ^{270}Hs based on these decay properties of ^{266}Sg. However, the work reported in [13] could not measure lifetimes of Sg isotopes and was not able to distinguish SF of ^{266}Sg from long-lived background. Sg chemistry experiments [15,32–34] could only detect isotopes with $T_{1/2} > 1$ s based on α-α and α-SF correlations. Single SF decays could not be unambiguously attributed to Sg isotopes. We believe that α-SF chains assigned to ^{266}Sg in [15,32–34] originated from ^{265}Sg-^{261b}Rf chains. ^{261b}Rf was unknown at that time. Two chains that were tentatively assigned to ^{270}Hs in [19,20] originated from ^{269}Hs in our opinion. SF decay of ^{266}Sg with $T_{1/2} = 444$ ms is not in contradiction with the data of any previous experiment.

In chain No. 14 an α-α-SF correlation was detected at the lower beam energy, but the decay properties differ from those observed for ^{269}Hs. The first α-particle that, due to the chemical separation should be attributed to a decay of Hs, has a high energy of $E_\alpha = 9.30$ MeV. The second α-particle has a relatively low energy of $E_\alpha = 8.20$ MeV and a lifetime of 149 s. The chain is then terminated by SF. Since the observed decay pattern is in agreement with predictions for ^{271}Hs and its daughters [7], we tentatively assign this decay chain to this nuclide and its daughters produced in the $3n$-evaporation channel. The large difference of the α-decay energies would be due to the crossing of the $N = 162$ neutron shell.

In chain No. 15 an α-SF correlation was observed similar as in chains No. 8, Nos. 11–13, but the α-particle energy is lower. This chain can be explained either as the decay of ^{270}Hs (with a low α-particle energy) or as a decay of ^{265}Sg after missing the α-particle from ^{269}Hs. No unambiguous attribution can be made.

In chain No. 7 an unusually low α-particle energy was detected and only one fragment from SF. This can be explained due to deposition of Hs on or near the nonactive surface on the edge of the detector, where there is a high probability for increased energy loss and to miss particles. No definite assignment is possible.

Cross sections of about 3 pb were measured for α-decaying ^{270}Hs at 136 MeV and of about 7 pb for α-decaying ^{269}Hs at 145 MeV beam energy with an estimated accuracy of a factor of about 3.

Decay properties derived from this work are presented in Table II. Errors correspond to a 68% confidence level [36] and do not include systematic errors. For ^{269}Hs and ^{265}Sg the half-lives and the measured α-energies are in good agreement with theoretical predictions [7] and are consis-

TABLE II. Decay properties of Hs and Sg nuclei observed in this work.

Z	A	Decay mode	Half-life	E_α [MeV]
108	269	α		9.07 ± 0.03
				8.92 ± 0.03
	270	α	22 s[a]	8.89 ± 0.03
106	265	α	$14.9^{+9.1}_{-4.1}$ s	8.68 ± 0.04
	266	SF	444^{+444}_{-148} ms	

[a]Half-life calculated using a phenomenological formula [35] based on the Q_α value deduced from our experimental data.

tent with results of previous experiments [14,19–21]. Decay properties of the even-even nuclei ^{270}Hs and ^{266}Sg have been established. The α-decay energy of doubly magic ^{270}Hs is in good agreement with theoretical calculations, which take into account shell stabilization of deformed nuclei. ^{270}Hs is the first experimentally observed even-even nucleus on the predicted $N = 162$ neutron shell. Our experimental data provide an important reference point for theoretical models and clearly show the enhanced nuclear stability at $N = 162$.

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