Decay properties of ^{265}Sg($Z=106$) and ^{266}Sg($Z=106$)

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The presently known most neutron-rich isotopes of element 106 (seaborgium, Sg), ^{265}Sg and ^{266}Sg, were produced in the fusion reaction ^{22}Ne+^{248}Cm at beam energies of 121 and 123 MeV. Using the On-Line Gas chemistry Apparatus OLGA, a continuous separation of Sg was achieved within a few seconds. Final products were assayed by α-particle and spontaneous fission (SF) spectrometry. ^{265}Sg and ^{266}Sg were identified by observing time correlated α-α-(α) and α-SF decay chains. A total of 13 correlated decay chains of ^{265}Sg (with an estimated number of 2.8 random correlations) and 3 decay chains of ^{266}Sg (0.6 random correlations) were identified. Deduced decay properties were $T_{1/2}=7.4^{+3.3}_{-2.7}$ s (68% c.i.) and $E_\alpha=8.69$ MeV (8%), 8.76 MeV (23%), 8.84 MeV (46%), and 8.94 MeV (23%) for ^{265}Sg; and $T_{1/2}=21^{+20}_{-12}$ s (68% c.i.) and $E_\alpha=8.52$ MeV (33%) and 8.77 MeV (66%) for ^{266}Sg. The resolution of the detectors was between 50–100 keV (full width at half maximum). Upper limits for SF of $\leqslant$35% and $\leqslant$82% were established for ^{265}Sg and ^{266}Sg, respectively. The upper limits for SF are given with a 16% error probability. Using the lower error limits of the half-lives of ^{265}Sg and ^{266}Sg, the resulting lower limits for the partial SF half-lives are $T^{\mathrm{SF}}_{1/2}(^{265}\mathrm{Sg})\geqslant 13$ s and $T^{\mathrm{SF}}_{1/2}(^{266}\mathrm{Sg})\geqslant 11$ s. Correspondingly, the partial α-decay half-lives are between $T^{\alpha}_{1/2}(^{265}\mathrm{Sg})=4.7$–16.5 s (68% c.i.) and $T^{\alpha}_{1/2}(^{266}\mathrm{Sg})=9$–228 s (68% c.i.), using the upper and lower error limits of the half-lives of ^{265}Sg and ^{266}Sg. The lower limit on the partial SF half-life of ^{266}Sg is in good agreement with theoretical predictions. Production cross sections of about 240 pb and 25 pb for the α-decay branch in ^{265}Sg and ^{266}Sg were estimated, respectively. [S0556-2813(98)05604-0]

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I. INTRODUCTION

The presently known most neutron-rich isotopes of element 106 (seaborgium, Sg), ^{265}Sg and ^{266}Sg, have recently been discovered in the reactions 116 MeV and 121 MeV ^{22}Ne+^{248}Cm using a gas-filled magnetic separator [1]. Due to the lack of an initial implantation signal in the silicon detectors, the half-lives of these two nuclides could not be measured. Only their α-decay energies were determined with an energy resolution of about 100 keV. They were in the range from 8.71 to 8.91 MeV for ^{265}Sg (4 events) and 8.54 to 8.74 MeV for ^{266}Sg (6 events). The authors estimated partial α-decay half-lives of 2–30 s for ^{265}Sg (assuming a hindrance factor between 1 and 3), and 10–30 s for ^{266}Sg from the measured α-decay energies. These estimated half-lives fit well with recent calculations [2–4]. An upper limit of $\leqslant$85% for the SF branch in ^{266}Sg was estimated [1]. In the course of the discovery experiment of element 112, two α-decay chains from ^{277}112 were observed, which ended in ^{257}No and ^{253}Fm [5]. These chains passed through ^{265}Sg with the following α energies and lifetimes for this nuclide: 8.77 MeV and 24.1 s, and 4.60 MeV (escape α particle) and 7.4 s, respectively. The absolute error in the α-decay energy was given as $\pm$20 keV. The two lifetimes yield a half-life of 11^{+20}_{-4} s (68% c.i.), in good agreement with predictions. In this work we used the same production reaction as in the discovery experiment (^{22}Ne+^{248}Cm) and the chemical separator OLGA (On-Line Gas chemistry Apparatus) [6,7] to isolate Sg and study its chemical properties [8] as well as the nuclear decay properties of its isotopes ^{266}Sg and ^{265}Sg from the $4n$- and $5n$-evaporation channels.

II. EXPERIMENTAL

In the course of two experiments a 950 μg/cm^2 ^{248}Cm target (95.7% ^{248}Cm, 4.2% ^{246}Cm) and a 690 μg/cm^2 ^{248}Cm target were bombarded at the GSI UNILAC accelerator with about 0.3 particle μA (2×10^{12} s^{-1}) ^{22}Ne ions. The second target contained about 70 μg/cm^2 Gd (30.6% enriched in ^{152}Gd) in order to simultaneously produce short-

lived W isotopes (a chemical analog of Sg). Both targets were prepared by electrodeposition on Be foils. The ^{22}Ne beam of the UNILAC passed through a 2.67 mg/cm^2 Be vacuum window, 0.65 mg/cm^2 N_2 cooling gas, and the 2.65 mg/cm^2 Be target backing before entering the Cm target. The beam energy in the target was 121 ± 1 MeV in the first and 123 ± 1 MeV in the second experiment. Recoiling nuclear reaction products were stopped in He gas loaded with carbon aerosols, which were generated by spark discharge. Attached to the surface of the aerosols, the reaction products were continuously transported within about 2 s along a 10 m long capillary (i.d. 2 mm) to the OLGA setup [7]. It consisted of a quartz chromatography column (2.5 m long, 1.3 mm i.d.) inside a commercial gas chromatography oven. The OLGA device allows chemical separation of volatile species within about 3 s. In the reaction oven (1000 °C) positioned at the entrance of the chromatography oven, 150 ml/min Cl_2 gas saturated with $SOCl_2$ and 2 ml/min O_2 gas were added in order to form volatile oxychlorides of Sg, a member of group 6 of the Periodic Table [8]. At the same time, the transporting graphite particles were stopped and destroyed on a quartz wool plug inserted into the reaction oven. In the subsequent isothermal chromatography part of OLGA, the quartz column was heated to temperatures between 300 °C and 400 °C, so that all elements of group 6 passed through the column essentially without delay, while all the actinides were retained. Also, the first two transactinide elements 104 (rutherfordium, Rf) and 105 (dubnium, Db; named hahnium, Ha, in earlier publications) are expected to be partly retained under these conditions. Volatile molecules, which passed through the column, were reattached to new aerosol particles (CsCl) and transported along a short capillary to the 64 position rotating wheel detection system ROMA [9]. Here, the products were deposited on 40 μg/cm^2 polypropylene foils mounted in every second position on the circumference of the wheel. All other positions remained empty. Every 10 s, the wheel was moved by a double step to transport the collected activity between pairs of 300-mm^2 PIPS detectors mounted in seven consecutive counting positions. In an event-by-event mode α particles with energies between 4.0 and 12.0 MeV, and SF decays (20–200 MeV) were recorded. The detection efficiency of a detector pair for detecting an α particle or a SF decay from the source was about 70%. The resolution was about 50 keV [full width at half maximum (FWHM)] for the detectors which look at the sample from the collection side (front detectors) and about 100 keV (FWHM) for the detectors which look onto the polypropylene foil from the rear side (back detector). The detector resolution of the front detectors was mainly determined by the mass of the deposited sample, whereas for the back detectors also the thickness of the polypropylene foils degraded the resolution. If in one of the back detectors an α particle with an energy between 8.5 and 9.1 MeV was observed—which might have been due to a decay of ^{265}Sg or ^{266}Sg with the α particle passing through the foil—the daughter mode (DM) was initiated. Here, the wheel was stepped by a single position only, so that all the samples were removed from the detection positions. Due to the α-recoil energy of about 0.1 MeV, the daughter nuclide (^{261}Rf or ^{262}Rf) was transferred with about 63% probability from the sample onto the opposite detector (front detector). During a waiting period of 120 s (first series of experiments, see Table I) or 200 s (second series of experiments), the α decay(s) of ^{261}Rf ($T_{1/2}=78$ s) [10] and/or its daughter ^{257}No ($T_{1/2}=26$ s) [11] or the SF decay of ^{262}Rf ($T_{1/2}=1.2$–2.1 s) [1,12] was assayed. The recoil probability of 63% was determined experimentally using ^{218}Po ($T_{1/2}=3.05$ m). Po behaves chemically very similar to the group 6 elements under the conditions of the experiment. Thus, the decay product ^{218}Po from a ^{222}Rn generator system, was attached to carbon aerosols and passed through the chromatography system under the same conditions as for the Sg experiment. The activity of the 6.00 MeV α line was measured. Then, all the samples were removed from the detection positions and the decay of the recoiled ^{214}Pb was measured via the 7.69 MeV α decay of its β^--decay granddaughter ^{214}Po. The DM stepping technique significantly reduces the background counting rate and thus the observation of random correlations. This technique has already been successfully applied in previous studies [13,14].

III. RESULTS AND DISCUSSION

The first series of experiments was performed with the 950 μg/cm^2 ^{248}Cm target. In these experiments the isothermal temperatures were kept at 300 °C (2.29×10^{16} ^{22}Ne particles), 350 °C (8.86×10^{16} ^{22}Ne particles), and 400 °C (1.48×10^{17} ^{22}Ne particles). In the second series of experiments the mixed 690 μg/cm^2 ^{248}Cm/70 μg/cm^2 Gd target was used and an isothermal temperature of 350 °C (1.96×10^{17} ^{22}Ne particles) was maintained. The α spectrum of all front detectors accumulated over a time period of 32 h in the second series of experiments at 350 °C is depicted in Fig. 1, as an example. The spectrum is dominated by α lines originating from isotopes of Po and Bi. Presumably, these nuclides are produced in multinucleon transfer reactions from Pb impurities in the Cm target. These elements are not or only partly retained in the chromatographic column. Except for ^{211m}Po and ^{212m}Po, all very short-lived Po activities are due to longer-lived Bi and/or Pb precursors. Also visible in the α spectrum are ^{227}Ac decay products, which were present as contaminants on some of the detectors in all of the experiments. The α lines around 4 MeV are from Dy and Ho isotopes, which were formed in multinucleon transfer reactions with ^{152}Gd. In the experiments at 350 °C the ^{248}Cm target contained an admixture of ^{152}Gd in order to simultaneously produce short-lived W isotopes, which were assayed by using standard γ spectrometry. By measuring the chemical yield of W the performance of the chemical separator system was continuously monitored. Dy and also Fm isotopes, observed in the α spectrum, indicate that lanthanides and actinides were not completely retained in the chromatographic column. Also indicated are the energy intervals where α decays of ^{266}Sg (8.41–8.85 MeV) and of ^{265}Sg (8.57–9.07 MeV) are expected. The energy windows for the decay of the Sg nuclides correspond to the average of the observed α energies from Ref. [1] $\pm3\sigma$ (8.82 ± 0.25 MeV for ^{265}Sg and 8.63 ± 0.22 MeV for ^{266}Sg). In the energy window 8.05–8.45 MeV α decays of the daughter and granddaughter of ^{265}Sg, ^{261}Rf, and ^{257}No, were expected. In this energy window 69 α-α correlated decay chains attributed to the decay of ^{261}Rf and its daughter ^{257}No were observed in

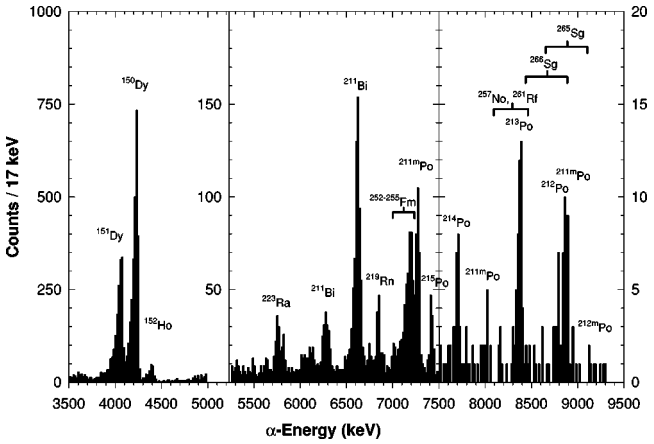

FIG. 1. Sum of α-particle spectra from all front detectors accumulated over 32 h (1.96×10^{17} ^{22}Ne particles) at an OLGA oven temperature of 350 °C.

the reaction ^{22}Ne+ ^{244}Pu [15]. No α-α correlations were observed above 8.45 MeV or between 7.6 and 8.05 MeV. Also, all daughter α decays in the discovery experiment of ^{265}Sg were observed within this energy window. However, in one of the decay chains of ^{277}112 a decay with E_α=8.52 MeV with a lifetime of 4.7 s was attributed to the decay of ^{261}Rf [5]. Currently it is not clear whether ^{261}Rf has indeed a weak α-decay line besides the known one at 8.29 MeV or if this decay energy is the result of conversion electron summing or a decay from an isomeric state in ^{261}Rf. Table I summarizes all observed α-α-(α) decay chains in the above mentioned energy intervals and all α-SF decay chains where the SF followed within 6.3 s (3 half-lives of ^{262}Rf [12]) after an α decay in the ^{266}Sg energy interval. Two different types of event chains are listed: decay chains that were observed in the low background environment of the DM, and decay chains which were observed while the wheel was not in DM, since the triggering α event was detected in the front detector and the α-recoil daughter remained on the sample. In DM, 4 decay chains attributed to the decay of ^{265}Sg and one chain attributed to ^{266}Sg were observed. Twelve decay chains attributed to ^{265}Sg and one chain attributed to ^{266}Sg were observed while the wheel was not in DM. For both categories of event chains the expected number of random correlations under the given energy and time windows are also listed. Random correlations were observed, when a sample, that by coincidence contained the fitting combination of Po and Bi nuclides, produced a series of α decays, that could not be distinguished from, e.g., a real ^{265}Sg decay sequence. The number of random correlations for, e.g., ^{265}Sg observed not in DM was evaluated as follows: Two hypo-

TABLE I. Correlated decay chains with E_α(mother)=8.57–9.07 MeV (^{265}Sg) and E_α[daughter(s)]=8.05–8.45 MeV (^{261}Rf, ^{257}No), and E_α(mother)=8.41–8.85 MeV (^{266}Sg) and E_{SF}(daughter)≥20 MeV (^{262}Rf) within 6.3 s.

Decay chain	E_1[a] (MeV)	t_1[b] (s)	E_2[c] (MeV)	Δt_2[d] (s)	E_3[e] (MeV)	Δt_3[f] (s)	Mode	Decay assignment	Isothermal temperature	N_R[g]
1	8.86	0.6	8.35	48.4			DM[h]	^{265}Sg→ ^{261}Rf or ^{257}No	300 °C	0.83
2	8.76	1.4	8.39	151.8			DM[h]	^{265}Sg→ ^{261}Rf or ^{257}No	350 °C[i]	
3	8.93	7.0	8.22	22.2			DM[h]	^{265}Sg→ ^{261}Rf or ^{257}No	350 °C[i]	
4	8.82	27.3	8.15	53.3			DM[h]	^{265}Sg→ ^{261}Rf or ^{257}No	300 °C	
5	8.81	2.8	8.36	31.0	8.11	14.8		^{265}Sg→ ^{261}Rf→ ^{257}No	400 °C	0.04
6	8.69	1.4	8.18	56.0				^{265}Sg→ ^{261}Rf or ^{257}No	300 °C	1.90
7	8.85	5.6	8.41	40.2				^{265}Sg→ ^{261}Rf or ^{257}No	350 °C[i]	
8	8.76	6.6	8.28	45.8				^{265}Sg→ ^{261}Rf or ^{257}No	350 °C	
9	8.77	6.8	8.22	25.5				^{265}Sg→ ^{261}Rf or ^{257}No	350 °C	
10	8.96	12.8	8.23	23.5				^{265}Sg→ ^{261}Rf or ^{257}No	350 °C	
11	8.85	19.1	8.35	0.5				^{265}Sg→ ^{261}Rf or ^{257}No	400 °C	
12	8.93	19.1	8.41	35.6				^{265}Sg→ ^{261}Rf or ^{257}No	350 °C[i]	
13	8.86	21.7	8.37	31.6				^{265}Sg→ ^{261}Rf or ^{257}No	300 °C	
14	8.95	34.0	8.22	31.2				(^{265}Sg→ ^{261}Rf or ^{257}No)	400 °C	2.90
15	8.97	43.8	8.20	1.5				(^{265}Sg→ ^{261}Rf or ^{257}No)	400 °C	
16	8.83	52.1	8.42	1.3				(^{265}Sg→ ^{261}Rf or ^{257}No)	400 °C	
17	8.52	48.9	SF[j]	2.8			DM[h]	^{266}Sg→ ^{262}Rf	400 °C	0.03
18	8.79	15.1	SF[j]	1.7				^{266}Sg→ ^{262}Rf	350 °C[i]	0.09
19	8.74	3.5	SF[j]	2.4				^{266}Sg→ ^{262}Rf	DC[k]	0.45

[a]Energy of the mother α particle (^{265}Sg or ^{266}Sg).
[b]Decay time (since beginning of measurement).
[c]Energy of the daughter α particle (^{261}Rf or ^{257}No).
[d]Time difference between the decay of the mother and the daughter nuclide.
[e]Energy of the granddaughter α particle (^{257}No).
[f]Time difference between the decay of the daughter and the granddaughter (^{261}Rf and ^{257}No).
[g]Expected number of random correlations for decay chains 1–4, 5, 6–13, 14–16, 17, 18, and 19.
[h]Event was registered in the daughter mode (DM).
[i]Event observed in the second series of experiments.
[j]Spontaneous fission (SF) with E_{SF}≥20 MeV.
[k]Decay chain was observed during a direct catch (DC) experiment with the tape detection system.

thetical nuclides P (parent) and D (daughter) decaying with α particles in the energy window defined for the parent ^{265}Sg and for the daughters ^{261}Rf and ^{257}No, respectively, were defined. A decay curve analysis was performed for α particles, that decayed with an energy within one of the energy windows defined for either P or D. Only α particles which were detected in the front detectors from samples that were measured for the full length of 70 s (uninterrupted by a DM) were included in the analysis. The following half-lives were determined: $T_{1/2}(\mathrm{P})=63.7^{+12.5}_{-9.2}$ s for the parent energy interval and $T_{1/2}(\mathrm{D})=61.3^{+21.6}_{-13.2}$ s for the daughter energy interval, respectively. These half-lives are the result of a combination of various Po and Bi nuclides, that decay with α-particle energies in the interesting energy windows. These were ^{211m}Po [$T_{1/2}=25.2$ s; $E_\alpha=8.885$ MeV (7.04%), 8.300 MeV (0.25%)], ^{212m}Po [$T_{1/2}=45.1$ s; $E_\alpha=9.080$ MeV (1.00%), 8.520 MeV (2.05%)], ^{212}Po [β^--decay product of ^{212}Bi and/or ^{212}Pb precursors; $E_\alpha=8.784$ MeV (100%)], and ^{213}Po [β^--decay product of ^{213}Bi and/or ^{213}Pb precursors; $E_\alpha=8.375$ MeV (100%)] (see Fig. 1). Since the wheel rotated for 360° (one full rotation) in 320 s, longer-lived activities accumulated over time. Thus, only apparent half-lives were observed, which differ from the known literature half-lives for the above mentioned nuclides. Accounting for the detector efficiency and the number of intermittent DM's, the actual number of nuclides P and D per sample was determined. Applying Poisson statistics, the number of samples containing the fitting combination of nuclides P and D (e.g., P and D for a random α-α correlation) that could produce a decay pattern, not distinguishable from, e.g., a real ^{265}Sg decay sequence, was calculated. A Monte Carlo procedure, that simulated the decay and detection of these nuclides, including the occurrence of DM's, yielded the probability that all of the nuclides contained in the sample were detected and that the detection occurred in the ''correct'' decay sequence (e.g., P decayed before D). Samples containing more than the minimum number of nuclides necessary for the observation of a correlation are occurring much less frequently (e.g., 2P and D), but the probability to randomly observe a fitting decay sequence (e.g., P→D) increases. Therefore, also samples containing one nuclide more than the minimum number of nuclides required to produce the sought after decay sequence were included in estimating the random contribution. Similarly, the number of random α-SF correlations was estimated. The decay analysis of α particles decaying in the energy window defined for ^{266}Sg yielded $T_{1/2}(\mathrm{P})=74.0^{+19.1}_{-12.9}$ s, whereas for fission fragments $\geqslant 20$ MeV an apparent half-life of $T_{1/2}(\mathrm{D})=50.2^{+26.1}_{-13.6}$ s was observed.

A different procedure had to be applied to estimate the random number of decay chains in the DM. First, one has to consider the possible sources for α decays during a DM. All observed decays must originate from nuclides that recoiled into the detectors, with α-recoil being the most probable recoil mechanism. In Fig. 2(a), all correlated DM events are shown (i.e., they were observed in the same detector pair as the α particle that initiated the DM.) In the correlated spectrum 4 decays were observed in the interesting energy range from 8.05 to 8.45 MeV. In order to assess the statistical significance of these events, the DM spectrum of the anticorrelated events is shown in Fig. 2(b) (i.e., DM events from all

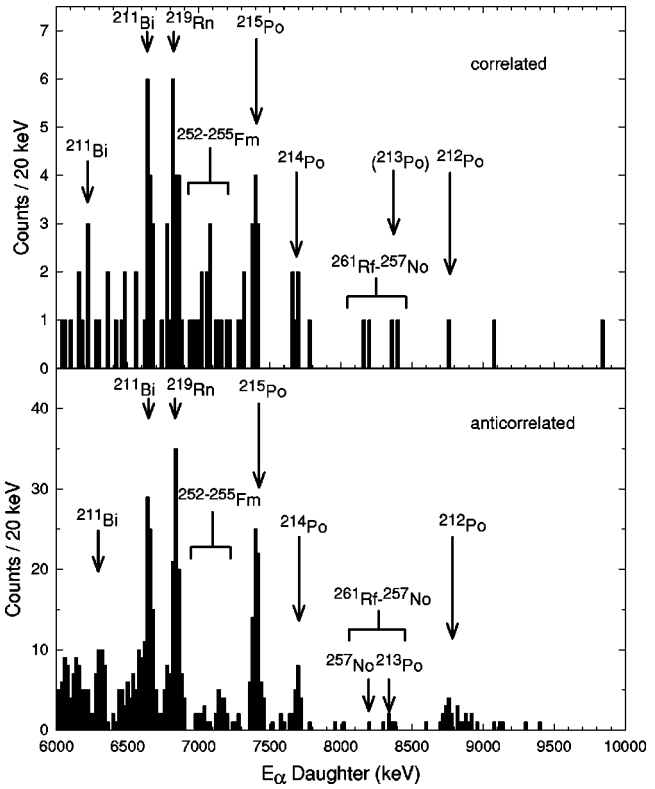

FIG. 2. (a) Sum of all α particles registered in the daughter mode correlated with the triggering mother α particle registered in the back detector of the same detector pair. (b) Sum of all α particles registered in the daughter mode in all those detector pairs which did not observe the triggering α particle.

detector pairs that did not observe the α particle that initiated the DM, but also recorded decays during DM intervals). The anticorrelated spectrum contains 6 times as much data as the correlated one, since there were a total of 7 detector pairs. The following activities were observed: (a) decay products of ^{227}Ac (^{219}Rn, ^{215}Po, ^{211}Bi) which was present as a contaminant on some of the detectors; (b) traces of ^{214}Po, a decay product of ^{218}Po, which has been used to test the chemistry and was used to calibrate the detectors; (c) traces of ^{212}Po, a decay product of Pb and Bi precursors and some $^{252-255}$Fm from direct catch experiments, where the activity was collected directly onto the wheel. In the region from 8.05 to 8.45 MeV a total of 6 events were detected. These α particles are from the decay of ^{261}Rf or ^{257}No (from cases where the mother ^{265}Sg α particle was missed, or where ^{257}No recoiled into the front detector as a daughter of ^{261}Rf) or from the decay of ^{213}Po. Therefore, the list mode data was searched for α particles of 8.05–8.45 MeV in the back detector preceding the DM (that occurred just by coincidence). Only the event at 8.19 MeV was preceded 67.5 s by a 8.30 MeV α particle. We therefore attribute this event to a ^{261}Rf-^{257}No decay sequence. The group of 5 α particles at 8.35 MeV was assigned to ^{213}Po (8.376 MeV), neglecting possible contributions of further ^{261}Rf or ^{257}No decays. Therefore, 0.83 of the observed 4 ''true'' correlations are expected to be random. For three of the four correlations the α-particle that initiated the DM was registered in the back detector of pair 1 (i.e., within the first 10 s of the measurement), reflecting the expected short half-live of ^{265}Sg. Due to the resolu-

tion of FWHM ≈50 keV in DM one can also assign the longer decay time of 27.3 s of decay chain 4 to a ^{265}Sg decay since the daughter energy of 8.15 MeV differs considerably from 8.376 MeV of ^{213}Po. The expected number of random correlations diminishes to 0.40 if only decay times up to the longest observed decay time are considered.

The count rate due to decays of Po and Bi nuclides in the energy regions defined for ^{265}Sg or ^{266}Sg did not depend on the selected isothermal temperatures. However, due to a cleaner target in the second series of experiments, the count rate in these regions was 3 to 4 times smaller compared to the first series of experiments. Except for the very short experiment at 300 °C isothermal temperature the yield of Sg was similar at all other temperatures. At 300 °C a considerably higher yield of Sg resulted, if all of the 4 observed decay chains were attributed to decays of ^{265}Sg. However, due to the very small number of detected events and the relatively short time measured at this temperature the errors associated with this result are very large. The analysis of a long experiment at 250 °C isothermal temperature is still in progress. The result of this experiment will be significant in establishing the chemical properties of Sg.

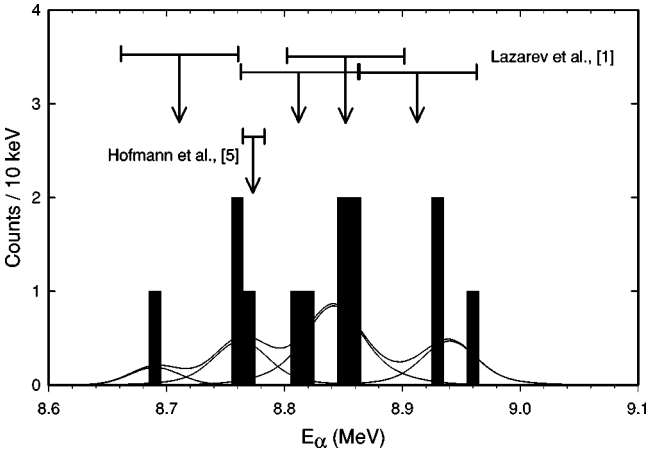

FIG. 3. Spectrum of all α particles attributed to the decay of ^{265}Sg. The energy of α decays observed in two other experiments are indicated by arrows. The horizontal error bars indicate the detector resolution (FWHM) in these experiments. Four α-decay lines with E_α=8.69, 8.76, 8.84, and 8.94 MeV were attributed to the decay of ^{265}Sg. The 4 Gaussian distributions reflect the detector resolution in this work.

A. α decay of ^{265}Sg

From the observed decay chains attributed to the decay of ^{265}Sg highest confidence can be assigned to the triple correlation (chain 5), which has a 4% probability to be entirely random (see Table I). For the 4 decays found in the DM (chains 1–4) the expected number of random events is 0.83. Finally, for the 11 correlated decay chains observed not in the DM (chains 6–16), 4.79 random correlations are expected. From a two component maximum likelihood decay curve analysis [16] to the decay times t_1 for decay chains 1–16, with a fixed half-life of the random component of $T_{1/2}$=63.7 s and a fixed number of 5.66 random correlations, a half-life of $7.4^{+3.3}_{-2.7}$ s was determined for ^{265}Sg. For the 11 α-α correlations observed not in the daughter mode (chains 6–16), the two-component decay behavior was clearly observed. Up to a decay time of 21.7 s, 8 decay chains were observed with an expected 1.90 random correlations, whereas for the last 3 events 2.90 random correlations were expected. Based on the half-life and initial activity of the short (^{265}Sg) component only 0.80 ^{265}Sg events with decay times longer than 21.7 s were expected. The last three decay chains were therefore considered as random. In Fig. 3, the 13 α events (including an estimated 2.34 random events) attributed to the decay of ^{265}Sg (E_1 from chains 1–13 from Table I) are plotted. The α spectrum covers an energy range of almost 300 keV. The α-decay energies observed in previous experiments [1,5] are indicated by arrows. The horizontal error bars correspond to the quoted detector resolutions in these experiments (FWHM). Due to the low statistics it is hard to determine how many α lines are present. Based on the following arguments 4 α-event groups at E_α=8.69±0.03 MeV (8%), 8.76±0.03 MeV (23%), 8.84±0.03 MeV (46%), and 8.94±0.03 MeV (23%) were assigned to the decay of ^{265}Sg. One group of 3 α events at 8.76 MeV coincides very well with the one event measured in the ^{277}112 decay chain which was measured with a very good detector resolution of FWHM=17 keV [5]. The absolute error of the α energy was given as ±20 keV [5]. The groups of α events at 8.82 and 8.86 MeV correspond well with the 2 α events observed by Lazarev *et al.* [1], i.e., 8.81 MeV and 8.85 MeV (measured with an energy resolution of ≈100 keV). Due to the 60 to 100 keV higher energy of these 6 events, compared to the group at 8.76 MeV, this group was assigned to a separate α line with E_α=8.84 MeV. In addition, a third group of α-decay energies is observed centered at 8.94 MeV. Actually, the one event observed at 8.91 MeV by Lazarev *et al.* [1] might also belong to this group. There is an indication of a fourth group centered at about 8.70 MeV. The one event at 8.69 MeV (chain 6) was observed in a front detector, which, due to the energy resolution of FWHM≈50 keV, considerably reduces the probability that it belongs to the 8.76 MeV group. Also, one of the events of Lazarev *et al.* [1] had an energy of 8.71 MeV. In order to verify visually whether this assignment of α lines is reasonable, a series of Gaussian distributions was generated for each of the 4 α lines. For instance, the group of 3 α events at 8.76 MeV consists of 2 α particles measured in the front detectors and 1 α particle measured in the back detector. Depending on the detector resolution, 2 Gaussians with FWHM=50 keV (front detectors) and 1 Gaussian with FWHM=100 keV (back detectors) were summed. The 4 individual distributions generated for E_α=8.69, 8.76, 8.84, and 8.94 MeV and their sum are shown in Fig. 3.

B. α decay of ^{266}Sg

Two correlated α-SF decay chains were observed during the chemistry experiments (see Table I). One of them was observed in the DM. For both decay chains the expected number of random correlations was calculated. Again, these two decay chains have a low probability to be random. During a direct catch (DC) experiment at 119 MeV bombarding energy, the products were transported with the gas-jet directly to a tape detection system [6]. The collected samples were stepped subsequently through 6 counting chambers.

With the tape detection system the samples could only be assayed from the front side. Throughout the DC experiment, 8722 samples were collected using a stepping time of 10 s. The accumulated beam dose was 1.46×10^{17} ^{22}Ne particles. The target contained 690 μg/cm^2 ^{248}Cm. In this experiment, one additional α-SF decay chain was observed within the energy range and time limits defined for ^{266}Sg. For the observed lifetime of the daughter nuclide of 2.4 s, the expected number of randomly correlated decay chains was calculated to 0.18. If the entire time window of 6.3 s (3 half-lives of ^{262}Rf [12]) defined for the daughter decay is considered, 0.45 random correlations are expected. Even though the probability of this event to be random is about 5 to 15 times higher compared to the two events from the chemistry experiments, this event was attributed to a ^{266}Sg decay chain as well. The three decay chains yield a half-life of $T_{1/2}=21^{+20}_{-12}$ s (68% c.i.) for ^{266}Sg. This value includes corrections due to the limited counting time of only 70 s (chemistry) and 60 s (tape) [17]. For the daughter nuclide ^{262}Rf a half-life of $T_{1/2}=2.5^{+2.4}_{-1.6}$ s (68% c.i.) was determined, again in good agreement with literature data [1,12]. Based on the resolution of the detectors two α-particle groups with $E_\alpha=8.52\pm0.03$ MeV (33%) and 8.77 MeV ±0.04 MeV (66%) were assigned to the decay of ^{266}Sg. Comparable α-decay energies between 8.54 MeV and 8.74 MeV with a similar detector resolution were determined in Ref. [1] for ^{266}Sg.

C. SF decay of ^{265}Sg and ^{266}Sg

According to theoretical calculations for ^{266}Sg, the partial half-lives against α decay and SF are expected to be rather similar [4,18]. Due to the odd neutron hindrance factor, the SF branch in ^{265}Sg is expected to be small. We tried to determine the branching ratios and the partial half-lives for SF for these nuclides from our data. The SF count rate varied strongly for the different runs, depending on the quality of the chemical separation. Considering the cross sections measured for multinucleon transfer reaction products [19], ^{256}Fm contributed most of the observed SF activity. By analyzing the α-count rates between 6.90–7.20 MeV (where decays of $^{252-255}$Fm were expected) for all individual runs, the contamination with Fm could be determined. Compared to a DC experiment, the contamination of the chemistry runs with Fm varied between 0.1 and 7.8%. In experiments with the mixed Cm/Gd target, a very similar contamination with ^{150}Dy was observed, which is an indication that the lanthanides, and therefore also the actinides (including ^{256}Fm), were much better retained in some runs than in others. The varying quality of the chemical separation can be explained by a slow degradation of the quartz wool plug in the reaction oven under the influence of the strong chlorinating reagents. The slow dissolution of the quartz wool allowed an increasing fraction of the transporting carbon aerosols to pass this filter and to travel through the chromatography column. Due to the very short time spent in the hot reaction oven, the nonvolatile species remained adsorbed on the aerosol surface and were not participating in the chromatographic process. In a subgroup of runs which on the average contained $\leqslant$1.2% Fm a total of 3 SF were observed. This subgroup of runs comprised 33.1% of the total of 9.3×10^{35} beam particles $\times$target atoms/cm^2 attained in all of the chemistry experiments and contained 5 decay chains of ^{265}Sg (chains 1, 4, 5, 6, 13), but none of the ^{266}Sg decay chains. However, since a Fm contamination of $\leqslant$1.2% still corresponded to a expected number of $\leqslant$10 SF originating from ^{256}Fm, the presence of SF events originating from other sources than ^{265}Sg or ^{266}Sg (^{262}Rf) cannot be excluded. Therefore, only upper limits were determined for the SF branches. The decay times of the 3 SF events were 24.3, 27.2, and 43.6 s, respectively. Taking into account the relatively short half-life of ^{265}Sg, a maximum of 2 of the 3 SF were attributed to a possible SF decay of this nuclide. Using a Monte Carlo simulation procedure, the SF branch in ^{265}Sg was estimated to be $\leqslant$35%. Alternatively, if all of the 3 SF were attributed to the SF decay of ^{266}Sg or its daughter ^{262}Rf, the SF branch in ^{266}Sg was estimated to be $\leqslant$82%. The upper limits for SF are given with a 16% error probability. A lower limit for α branching of $\geqslant$15% ($\leqslant$85% SF branching) for ^{266}Sg was given by Lazarev *et al.* [1]. A SF branch of 62^{+22}_{-24}% in ^{266}Sg was evaluated from the results of an aqueous chemistry experiment with Sg [20], using preliminary cross section and half-life data from this work. Both values are in agreement with our data. No SF branch has previously been determined for ^{265}Sg. Using the lower error limits of the half-lives of ^{265}Sg and ^{266}Sg, the resulting lower limits for the partial SF-decay half-lives are $T^{SF}_{1/2}(^{265}\text{Sg})\geqslant13$ s and $T^{SF}_{1/2}(^{266}\text{Sg})\geqslant11$ s, respectively. Correspondingly, the partial α-decay half-lives are between $T^{\alpha}_{1/2}$ (^{265}Sg)=4.7–16.5 s (68% c.i.) and $T^{\alpha}_{1/2}$ (^{266}Sg)=9–228 s (68% c.i.), using the upper and lower error limits of the half-lives of ^{265}Sg and ^{266}Sg. In Fig. 4, the experimentally determined partial half-lives for α and SF decay for ^{260}Sg [21,22] and ^{266}Sg (this work) are compared with theoretical calculations of Smolańczuk, Skalski, and Sobiczewski [4,18]. The accuracy of the theoretical calculations is remarkable. Our data clearly confirms the predicted enhanced nuclear stability near $N=162$ and $Z=108$.

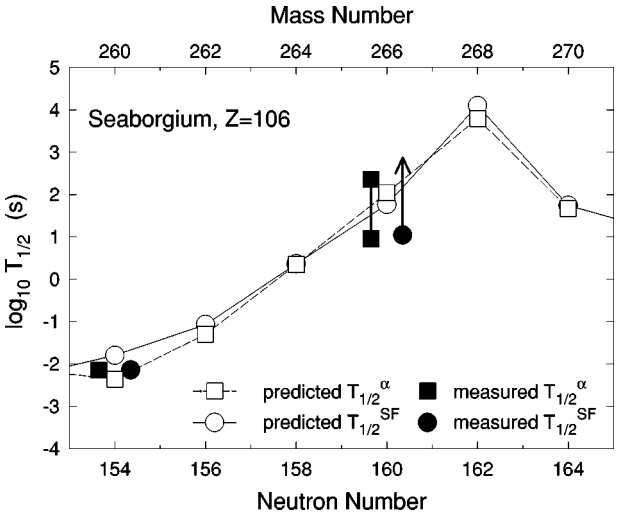

FIG. 4. Predicted partial half-lives for α decay (Ref. [4]) and SF decay (Ref. [18]) of the even-even Sg isotopes. The experimental values for ^{260}Sg (Refs. [21] and [22]) and the results for ^{266}Sg from this work are shown for comparison.

D. Cross sections

Our experiments were not intended to yield precise cross sections, since several yields in the OLGA system have not

been determined accurately throughout the experiment. However, on the basis of yields that were typically observed in test experiments with W isotopes (gas-jet transport=40%; chemical yield=60%) and counting efficiencies (α and SF counting efficiency=70%) cross sections of about 240 pb for the production of α-decaying ^{265}Sg and of about 25 pb for the production of α-decaying ^{266}Sg were deduced for a ^{22}Ne projectile energy between 120 and 124 MeV. The cross sections were estimated to be accurate within about a factor of two for ^{265}Sg and within a factor of three for ^{266}Sg. These cross sections are in agreement with values given in Ref. [1]. For the single decay chain observed in the direct catch experiment at a ^{22}Ne-projectile energy of 118 to 120 MeV, a ^{266}Sg production cross section of about 60 pb was calculated.

IV. CONCLUSIONS

We were able to confirm the decay properties of ^{265}Sg and ^{266}Sg as they were observed in the discovery experiment by Lazarev *et al.* [1], using the same production reaction ^{248}Cm(^{22}Ne, 4,5n)^{266,265}Sg and our chemical separator system OLGA. In addition, we have measured the half-lives of both nuclides. We determined upper limits for the SF branches of ^{265}Sg and ^{266}Sg and established lower limits for the partial SF-decay half-lives. While the lower limit for the partial SF half-life in ^{266}Sg is not significantly different from the values obtained in the discovery experiment, or from Ref. [20], a lower limit for the partial SF half-life in ^{265}Sg has been established in this work. An accurate value of the partial SF half-life of ^{266}Sg is of special interest for the test of theoretical models. Smolańczuk *et al.* [4,18] so far offered an unprecedented accuracy in predicting partial α- and SF-decay half-lives of heavy and superheavy nuclides. They predicted an enhanced nuclear stability near the deformed shells $N=162$ and $Z=108$, which now has been confirmed experimentally. The cross sections estimated for the production of ^{265}Sg and ^{266}Sg are in good agreement with values given by Lazarev *et al.* [1]. The current work signifies the first successful chemical separation of element 106, seaborgium, during which its two heaviest known isotopes were unambiguously identified by their nuclear decay properties [8]. We believe that for the discovery of some of the predicted longer-lived isotopes of heavy elements ($T_{1/2}\gtrsim 1$ s) the sensitivity of radiochemical methods may present a viable alternative to physical separator systems.

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