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Short note

The new isotope ^{270}110 and its decay products ^{266}Hs and ^{262}Sg

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Abstract. The even-even nucleus ^{270}110 was synthesized using the reaction ^{64}Ni + ^{207}Pb. A total of eight α-decay chains was measured during an irradiation time of seven days. Decay data were obtained for the ground-state and a high-spin K isomer. The new nuclei ^{266}Hs and ^{262}Sg were identified as daughter products after α-decay. Spontaneous fission of ^{262}Sg terminates the decay chain. The measured data are in agreement with calculations using the macroscopic-microscopic model and with self-consistent HFB calculations with Skyrme-Sly4 interaction.

PACS. 21.10.Dr Binding energies and masses – 23.60.+e Alpha decay – 25.70.-z Low and intermediate energy heavy-ion collisions – 25.85.Ca Spontaneous fission – 27.90.+b $220 \leq A$

1 Introduction

Synthesis and investigation of heavy even-even nuclei provide especially clear data for comparison with theoretical predictions. The absence of unpaired nucleons results in unhindered α-decay and spontaneous fission. Also the low-energy level scheme is expected to be relatively simple. However, the synthesis of even-even nuclei is more difficult by the fact that in fusion reactions with ^{208}Pb and neutron-rich projectiles 2 neutrons must be evaporated, or the target must be replaced by ^{207}Pb. In both cases the measured cross-sections for the synthesis of nuclei beyond rutherfordium revealed a stronger decrease than in 1n reactions using ^{208}Pb targets. The latter reaction was used in experiments aiming at the synthesis of new elements (an overview of recent experiments is given in ref. [1]). Consequently, only few even-even nuclei are known beyond rutherfordium with ^{264}Hs being so far the heaviest one produced in reactions with ^{207}Pb targets [2]. Evidence of heavier even-even nuclei (^{292}116) was obtained from recent work in Dubna [3]. In this work we present results obtained in an experiment at the GSI SHIP aiming at the synthesis of the even-even nucleus ^{270}110 using the reaction ^{64}Ni + ^{207}Pb.

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2 Experiment and results

The beam of $^{64}Ni^{9+}$ was prepared from enriched material at the High Charge State Injector (ECR-ion source) of the UNILAC. The irradiation started on October 29, 2000. During a period of 7.3 days we collected a beam dose of 1.3×10^{18} ions. The beam energy was 317 MeV. It was chosen so that the compound nucleus produced in the center of the target layer would have an excitation energy of 14.0 MeV. This energy was estimated from our previous measurements of excitation functions [1] to be close to the maximum production rate of ^{270}110.

The experimental set-up consisting of rotating target wheel, separator SHIP, detector, and data analysis was the same as in our previous experiments, except an additional electronic circuit which allowed for switching off the beam within 50 μs after an implanted residue was detected by coincidence of energy and time-of-flight signal. In a subsequent first time window of 10 ms a preset number of α-particles (in this experiment one) was counted which then prolonged the beam-off period up to the expected measurable end of the decay chain. In our experiment 200 s were chosen.

The ^{207}Pb target was prepared from enriched (92.4 %) material. Metallic lead was evaporated on a carbon foil (36 μg/cm^2) to a thickness of 435 μg/cm^2. The lead was then covered by a carbon foil of 10 μg/cm^2 thickness. The thicker carbon foil was oriented up-stream, and a charge

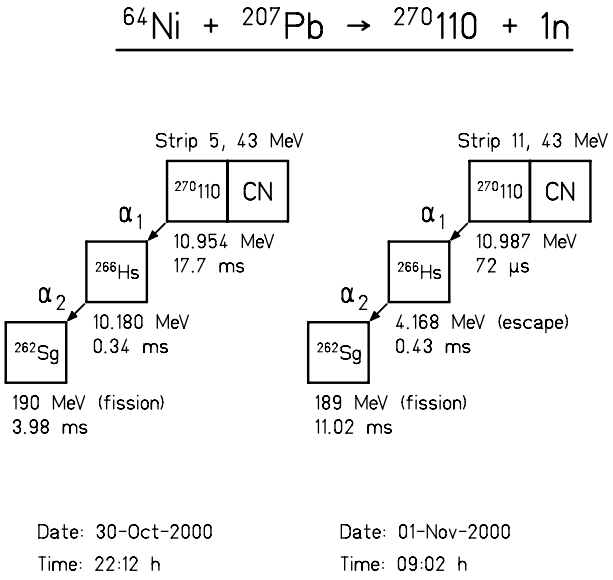

Fig. 1. Two representative decay chains observed in irradiation of a ^{207}Pb target with ^{64}Ni projectiles. The chain on the left side starts with a relatively long-lived α-decay of ^{270}110 which is attributed to a high-spin K isomer. The chain on the right side represents the decay of the short-lived ground state.

Table 1. Alpha and spontaneous fission energies and lifetimes from the eight decay chains of ^{270}110 in the order of increasing lifetime of the first α-decay. Energies are given in MeV, lifetimes in ms. The number n denotes the sequence of detection in the experiment.

	^{270}110		^{266}Hs		^{262}Sg	
n	E_α	τ	E_α	τ	E_{sf}	τ
4			0.578[a]	0.46	227	2.00
6			10.306[b]	5.40	177	33.91
5	10.987[b]	0.07	4.168[a]	0.43	189	11.02
3	11.075[b]	0.18	10.196	0.87	193	10.26
1	1.925[a]	0.20	10.173	2.79	164	8.84
7	11.151[c]	2.00	10.171	18.22	199	13.06
8	12.147[b]	10.35	10.281[b]	9.63	215	7.77
2	10.954	17.71	10.180	0.34	190	3.98

[a]escape α, [b]ΔE_α = 90 keV (FWHM), [c]218 keV γ coincident.

equilibration foil (60 μg/cm^2 carbon) was mounted downstream at a distance of 16 cm from the target.

The energy resolution of the detector for fully stopped α's was 20 keV (FWHM) and for escape α's stopped in the back detectors (see ref. [1]) 90 keV. Due to a correction for pile-up on the tail of the signal from a residue implanted with high energy, we estimated a similar uncertainty for the energy of α's following an implantation within 0.4 ms.

During the experiment we observed eight decay chains. The decay data are presented in table 1. Two representative chains are shown in fig. 1. One additional chain was identical to previously measured chains from ^{271}110. It was attributed to the 1n channel from reaction with the ^{208}Pb-target contamination of 5.5 %.

All eight chains ended with a high-energy fission event. Six of them are each preceded by two α-particles, two (no. 4 and 6) by only one. The chains started with an implantation signal (time-of-flight and energy in coincidence) which switched off the beam. However, in the case of chain 2, 4 and 8 the trigger conditions for switching off the beam were not fulfilled. These chains were found in the off-line analysis. All signals attributed to one decay chain occurred in the same detector strip at the same vertical position within a range of Δy = 0.5 mm (FWHM). The longest period from implantation to fission was 39.3 ms (chain 6).

A cross-section of $\sigma = (13 \pm 5)$ pb was measured for the production of all eight events. It was determined using a calculated efficiency of SHIP of 40 %. The error bar represents the statistical uncertainty only, systematic deviations may change the cross-section value up to a factor of two.

3 Discussion

We consider first the six longer chains. Their assignment to a nucleus (assignment of A and Z) is straightforward, because most of the possible candidate nuclei near the compound nucleus ^{271}110 are sufficiently well known and can be excluded. The decay chains from reaction channels p, 2p, pn and 2n include longer living α emitters which were not measured. The αn channel would result in the evaporation residue ^{266}Hs. This nucleus as well as the daughter ^{262}Sg are unknown, but the fission events at the end of the chain would fit well to the known fissioning nucleus ^{258}Rf. However, the αn channel is excluded due to the low excitation energy (14.0 MeV) of the compound nucleus and the low transmission through SHIP for this channel which is reduced by a factor of eight compared with the transmission for xn channels. Therefore we assign the six longer chains to the new even-even nucleus ^{270}110 produced after one neutron emission. The two subsequent α-decays populate ^{266}Hs and ^{262}Sg, where the chains terminate by fission.

More difficult is the assignment to certain levels of the nuclei. The α-decays of ^{270}110 occur within two groups of significantly different lifetime. The α's (1, 3, 5) have a mean value τ = 0.15 ms, whereas the α's (2, 7, 8) decay with τ = 8.6 ms. The lifetime of the events is plotted in fig. 2a together with two fitted (least-squares fit) universal lifetime curves [4]. (Throughout the discussion we prefer to use the lifetime, because this is the directly measured quantity from the decay. At the end of the paper we convert the mean values into the commonly used half-lives. There we also give the statistical error bars.)

The decay data of the short-lived group reveal similarities beyond their common lifetime. The energy of the first α-decay of chain 3 and 5 agrees within the error bar. In two cases (chain 1 and 3) the α's of the daughter decay were fully stopped in the detector. Their energies (10.173 and 10.196 MeV) agree within the 20 keV detector resolution. The average lifetime τ (determined from the mean of the logarithm) of all three daughter decays is 1.0 ms.

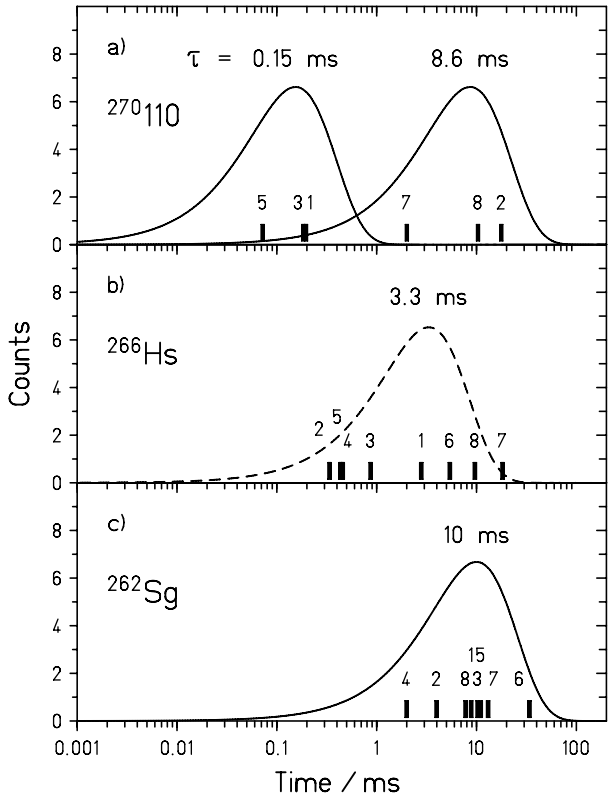

Fig. 2. Time distribution of the subsequent α-decays (a,b) and fission events (c) measured in the reaction ^{64}Ni + ^{207}Pb. The curves represent the density distribution (arbitrary ordinate scale) of counts in a radioactive decay on a logarithmic time scale with logarithmically increasing channel width [4]. The position of the curve determines the lifetime, it was adjusted to the data by a least-squares analysis. The dashed curve in plot b) indicates that the data are also compatible with two lifetimes of 0.5 and 9 ms (see text). The numbers from 1 to 8 assign the events to the measured decay chains.

The grand-daughter (^{262}Sg) decays by spontaneous fission with $\tau = 10$ ms.

Calculated partial α lifetimes [5] for ^{270}110 and ^{266}Hs using the measured energies of 11.03 and 10.18 MeV, respectively, and zero angular momentum are 0.11 and 3.2 ms. Both values agree within the statistical uncertainties with the experimental values. Therefore we assign these α-decays to the $0^+ \rightarrow 0^+$ ground-state α transitions from ^{270}110 $\rightarrow$ ^{266}Hs $\rightarrow$ ^{262}Sg.

The decay properties of the longer lived α-decays (chain 2, 7 and 8) are more complex. Despite a common lifetime of 8.6 ms, the α energies are all different, 10.95 and 11.15 MeV, both measured with their full energy and thus high precision in the stop detector, and 12.15 MeV, measured as coincidence of signals from the stop detector and the backward detector. In addition, the 11.15 MeV signal was in coincidence with a 218 keV γ signal in the Ge detector.

In order to make an assignment of the long-lived group, we first calculated the α lifetimes assuming retardation by angular momentum. The result is presented in table 2.

Table 2. Calculated partial α-decay lifetimes for decays of ^{270}110 including angular-momentum hindrance. The transmission probability for α's was calculated using the potential of ref. [5]. Energies are given in MeV, lifetimes in ms, n is the chain number and Δl is the difference of angular-momentum quantum number between parent and daughter state.

n	E_α	$\tau_{\rm exp}$	$\tau_{\rm calc}$	Δl
7	11.151	2.00	0.06	0
			1.1	6
			9.1	8
8	12.147	10.35	0.0005	0
			0.97	10
			17	12
2	10.954	17.71	0.16	0
			3.2	6
			26	8

The mean experimental lifetime of 8.6 ms is reproduced by α transitions with $\Delta l \approx 8$ (chain 2 and 7) and $\Delta l \approx 12$ (chain 8). Assuming one isomeric state as parent for all three decays, the α energy of chain 8 indicates an energy for this isomer of at least 1.1 MeV above the ground state.

High-spin isomeric levels originate in even-even nuclei from intruder states (see, *e.g.*, ^{156}Hf and ^{158}W [6]) or in the case of deformed nuclei from two quasiparticle high-spin configurations (K isomers). Examples in the region of heavy elements are the isomers in ^{250}Fm, ^{254}No [7] and ^{256}Fm [8].

On the basis of a long-term theoretical investigation of superheavy elements (details of the applied model are published elsewhere [9]), calculations were performed for the nuclei ^{266}Hs and ^{270}110. The result was that in ^{270}110 the lowest two neutron quasiparticle states are formed at energies of 1.31 and 1.34 MeV and in ^{266}Hs at 0.90 and 0.94 MeV. These states are created by breaking a pair in orbits with the asymptotic Nilsson quantum numbers $\nu[613]_{7/2^+}$ and $\nu[615]_{9/2^+}$, respectively, and raising, in both cases, the neutron with spin and orbital angular momentum in the same direction into the orbit $\nu[725]_{11/2^-}$. The resulting spin and parity of the configuration are 9^- and 10^-, respectively.

The rotational behavior of deformed heavy nuclei was recently investigated by Muntian *et al.* [10] and Sobiczewski *et al.* [11]. Using their energies obtained for the 2^+ and 4^+ rotational levels in ^{270}110 and ^{266}Hs and the $E(I) \sim I(I+1)$ law, we calculate for the 8^+ and 10^+ rotational levels energies of 572 and 874 keV (^{270}110) and 550 and 840 keV (^{266}Hs). Gamma transitions of multipolarity 1 or 2 from the $K = 9$ or 10 quasiparticle states into the rotational band are expected to be strongly reduced due to the high degree of K forbiddeness. We, therefore, tentatively assign the decays with the 8.6 ms lifetime to the decay of one of the states with K quantum number

9 or 10. The energy of the isomer is at 1.13 MeV, about 0.2 MeV less than calculated.

The α transition (chain 8) to the 0^+ ground state in ^{266}Hs occurs with $\Delta l = 9$ due to the change of parity. A calculated lifetime for a $\Delta l = 9$ transition is 0.23 ms. A required hindrance factor of 37 due to a configuration change seems reasonable.

Two possibilities exist for the assignment of the 10.95 MeV α-decay (chain 2). 1) The α-decay could be a transition from the K isomer in ^{270}110 to the analogue isomer in ^{266}Hs. In this case the energy of the level would be at 1.21 MeV, about 0.3 MeV higher than calculated. 2) The K isomer decays via γ/IC branching into the ground-state rotational band. Then the α energy of 10.95 MeV would be due to the ground-state α-decay, but the measured lifetime would be determined by the lifetime of the isomer. The energies of the directly measured ground-state decay (chain 3 and 5) are not accurate enough to favor assumption 2), although they are still in agreement with the more precise energy value of chain 2.

The α-decay in chain 7 was coincident with a 218 keV γ signal in the Ge detector which rules out the possibility of a ground-state to ground-state decay. For this decay we propose a transition into an excited level in ^{266}Hs, which could be the analogue K isomer, or a high spin level of the ground-state rotational band. It is interesting to note that the energy of the γ signal is close to the calculated transition energy of 229 keV from the 8^+ to 6^+ rotational level in ^{266}Hs. For this transition a conversion coefficient of about 1 is expected [12].

Four α-particles of the decay of ^{266}Hs were measured with full energy and hence with high precision in the stop detector (chain 1, 2, 3, 7). Their mean energy is 10.180 MeV. Using this energy we calculate a lifetime of 3.2 ms for a $\Delta l = 0$ transition. This value is in agreement with the mean lifetime of 2.0 ms determined from the four events. Therefore we assign also the α-decays at 10.18 MeV of chain 2 and 7 to the ground-state to ground-state transition from ^{266}Hs to ^{262}Sg.

The α-particle in the case of chain 5 escaped from the detector and in the case of chain 8 the accuracy is reduced due to summing of the partial energies. The total energy of 10.28 MeV, however, is still in agreement with the ground-state α-decay of 10.18 MeV. In both cases the lifetime agrees with 2.0 ms determined from chains 1, 2, 3 and 7. We assign the two events 5 and 8 also to the ground-state decay of ^{266}Hs.

Striking is the long lifetime of 18 ms for the decay of ^{266}Hs in the case of chain 7. Similarly, the corresponding lifetimes of chain 6 and 8 are unusually long as visualized in fig. 2b. Indeed, a chi-square analysis of the data resulted in two, however, not well-separated minima of chi-square at $\tau = 0.5$ and 9 ms. On the basis of the present data, however, the assignment of α-decays into an isomeric state in ^{266}Hs seemed us too vague, although such transitions seem to be possible on the basis of the theoretical investigation.

The grand-daughter nucleus ^{262}Sg decays by fission with a mean lifetime of 10 ms. The fission events of all eight decay chains were considered. They are plotted together with the fitted lifetime curve in fig. 2c.

A comparison with calculated fission lifetimes results in a shorter experimental value by about a factor of ten. The calculated lifetime given by Smolanczuk *et al.* [13] is 120 ms. Deviations between experimental and calculated fission lifetimes are much less in the case of the known isotopes ^{258}Sg and ^{260}Sg and the known fissioning isotopes of rutherfordium. The slightly increased fission probability of ^{262}Sg is probably related to a less pronounced shell-correction energy near the middle between $N = 152$ and 162 which mark the neutron numbers of nuclei with local minimal negative shell-correction energy.

Fission was not observed for ^{270}110 and considering only the six longer chains, also not for ^{266}Hs. In the case of ^{270}110 lower limits of 0.3 ms and 17 ms for the partial fission lifetime were deduced from the experiment for the ground state and the isomeric state, respectively. A calculated partial fission lifetime for the ground state is 780 ms [13]. The lower limit for ^{266}Hs is 10 ms, and the calculated partial fission lifetime is 2.3 s [13]. Taking into account an uncertainty of the calculated fission lifetimes of a factor of ten, then the largest fission branching that we can expect for the ground state of ^{270}110 and ^{266}Hs is 0.2 % and 1.4 %, respectively. For this reason we assign the two fission events observed in chain 4 and 6 after only one α-decay not to ^{266}Hs. Our interpretation is that in the case of short lifetime (< 50 μs) the signal from the first α-decay was lost due to pile-up on the tail of the high signal amplitude (≈ 40 MeV) of the implanted residue. This interpretation is also compatible with the fact that the beam was not switched off by α's occurring within 50 μs after implantation of the residue, as it could have happened in the case of chain 4. If, indeed, the decay of ^{270}110 in chain 4 and 6 happened within 50 μs, then the real lifetime of ^{270}110 could be shorter up to about 50 %.

The implantation energy could be significantly reduced using degrader foils in front of the detector. In our experiment, however, we preferred direct implantation, because a deep implantation provides optimum conditions for the measurement of the total kinetic energy of fission events.

The energy of the evaporation residues was reduced after the target only by the cover foil, the converter foil and six foils from the time-of-flight detectors which amounted to a total thickness of 260 μg/cm^2 carbon. From the kinematics of the reaction and the energy loss in carbon [14], we calculated an implantation energy of 58 MeV into the detector. The measured average signal height was 41 MeV using the energy of implanted projectiles for calibration.

We estimated an implantation depth of about 9 μm into the Si detector using the range program SRIM [14]. At this depth only about 30 % of the fission fragments escape from the active detector volume which was probably the case for chain 1 and 6. From the other chains we determine a mean signal height of 202 MeV using the calibration by beam particles. After correcting for an additional pulse-height deficit we get for the fission of ^{262}Sg a total kinetic energy of (222 $\pm$ 10) MeV. This energy is in good agreement with data from fission systematics [15].

The α energy for the ground-state decay of ^{270}110 and ^{266}Hs is 11.03 and 10.18 MeV, respectively. Both values are in agreement with the values of 11.07 and 10.05 MeV resulting from the calculation by Smolanczuk [16] on the basis of the macroscopic-microscopic model. The α energies obtained from self-consistent HFB calculations are 10.72 and 10.04 MeV.

Using the predicted α energy of 9.45 MeV for the nucleus ^{262}Sg [16], we determine a partial α lifetime of 66 ms. From this value and our measured total lifetime of 10 ms follows an α branching of 15 %. From the non-observation of α-decay of ^{262}Sg and the measured eight fission events follows an experimental upper limit for α-decay of 22 %. These data suggest that in 2 or 3 times longer irradiation the chances are high for the observation of an α-decay branch of ^{262}Sg.

The measurement of reaction cross-sections is the most important task in studies of superheavy elements. Among these studies the investigation of neighboring reaction channels is of special interest, because it provides a controlled minimum change of the reaction process and thus allows for comparison with already known data of already "understood" reactions.

Recently, a number of cross-section calculations were performed and published [16–22]. In general, the models reproduce well the measured data of cold fusion reactions up to element 112. Predictions for the reaction ^{64}Ni + ^{207}Pb were given in refs. [16,21]. In ref. [16] a maximum cross-section of 2.0 pb was calculated at an excitation energy of 11.7 MeV. Almost identical values were obtained in ref. [21]. Our experimental value is (13 ± 5) pb at an excitation energy of 14.0 MeV. This value is comparable to the value of (15 ± 7) pb measured at 12.1 MeV excitation energy for the synthesis of ^{271}110 in the reaction ^{64}Ni + ^{208}Pb.

A number of differences between reactions resulting in odd or even compound nuclei of even elements is qualitatively obvious, *e.g.*, pairing energy, specialisation energy due to the odd particle and level density. Quantitatively their influence on the fusion cross-section was studied in refs. [16,21]. One phenomenon, however, namely the occurrence of isomeric states in the de-excitation cascade is difficult to predict for specific reactions. It may modify the survival probability significantly to smaller or larger values. This depends on the structure of the isomer which may lower or increase the fission barrier. In our case an isomeric ratio of 1 was measured for the synthesis of ^{270}110 in the ground state and in a high-spin ($K = 9$ or 10) isomeric state.

A side effect is connected with the decay of short-lived isomeric states which has significant influence on the transmission through an electromagnetic separator. If an isomer exists and decays downstream the charge equilibration foil, which means at lifetimes of about 0.02 to 1 μs, then the ionic charge state could be significantly changed due to conversion processes. As a result, the transmission through the separator would be reduced. In general, the γ cascade after neutron emission reaches the ground state faster in the case of even-even nuclei, *i.e.* still in or shortly after the target, so that the synthesis of even-even nuclei may be favored concerning the separation by SHIP.

4 Summary and outlook

In irradiation of a ^{207}Pb target with ^{64}Ni projectiles we synthesized the new even-even nucleus ^{270}110. A total of eight α-decay chains was measured during an irradiation time of seven days. The ground state of ^{270}110 decays by α emission with an energy of (11.03 ± 0.05) MeV and a half-life of $(100^{+140}_{-\ 40})$ μs. In addition, we measured an isomeric level in ^{270}110 which decays with a half-life of $(6.0^{+8.2}_{-2.2})$ ms. Alpha rays of energy (10.95 ± 0.02), (11.15 ± 0.02) and (12.15 ± 0.05) MeV were attributed to the decay of the isomer. A tentative assignment of the 12.15 MeV α to a transition into the ground state of ^{266}Hs results in an energy of the isomer at 1.13 MeV. The spin of the isomer was estimated from retardation of α-decay probability to be approximately (10 ± 2) $\hbar$. A γ/IC branching of ≈ 30% to the ground state seems possible, but could not be definitely established.

The decay properties of the ground state of ^{270}110 are in agreement with predictions of the macroscopic-microscopic model and with self-consistent Hartree-Fock-Bogoliubov calculations with Skyrme-Sly4 interaction. The HFB calculations resulted also in two excited levels, one of them could be the origin of the isomeric state. Their configuration and energy is $\{\nu[613]_{7/2^+}\ \nu[725]_{11/2^-}\}_{9^-}$ at 1.31 MeV and $\{\nu[615]_{9/2^+}\ \nu[725]_{11/2^-}\}_{10^-}$ at 1.34 MeV.

The new nuclei ^{266}Hs and ^{262}Sg were identified as members of the α-decay chain. The nucleus ^{266}Hs decays by α emission with an energy of (10.18 ± 0.02) MeV and a half-life of $(2.3\ ^{+1.3}_{-0.6})$ ms. However, it is possible as indicated by the decay data, that the α-decay has two components with half-lives of $(0.35\ ^{+0.28}_{-0.11})$ and $(6.3\ ^{+8.6}_{-2.3})$ ms. In that case an isomeric level would exist also in ^{266}Hs which could originate from states analogue as in the case of ^{270}110. Their energies in ^{266}Hs are predicted to be at 0.90 and 0.94 MeV using HFB calculations. For both nuclei fission was not observed. Using calculated fission half-lives, we estimated fission branchings of 0.2 and 1.4 % for the nuclei ^{270}110 and ^{266}Hs, respectively.

The nucleus ^{262}Sg decays by fission with a half-life of $(6.9\ ^{+3.8}_{-1.8})$ ms and a total kinetic energy of the fission fragments of (222 ± 10) MeV. Alpha-decay was not measured, an upper limit for the α branching is 22 %. This value is in agreement with an estimate of 15% alpha branching, using a half-life deduced from a calculated value for the α energy of ^{262}Sg.

The measured cross-section of (13 ± 5) pb was unexpectedly high. It is shared equally between ground state and isomeric state.

Future experiments at longer irradiation time and higher beam dose will certainly provide a more detailed decay scheme and low energy level scheme of ^{270}110 and its daughter nuclei. Pulse-shape analysis and the use of degrader foils in front of the detector will allow for a more

precise determination of the α energy in the case of single events and short lifetime. Coincidence experiments using large Ge detectors are promising to search for transitions within the rotational band in ^{266}Hs after α-decay of ^{270m}110. The low energy rotational levels can be studied via fine-structure α-decay. The measurement of the excitation function will provide data on the population of ground state and isomeric state. The daughter nucleus ^{266}Hs could possibly be studied directly using the radiative capture reaction of ^{58}Fe and ^{208}Pb. An important next step using ^{207}Pb target is the investigation of ^{276}112. The result will demonstrate if the synthesis of even-even nuclei in cold fusion reactions could be applied also for still heavier systems.

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