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Detailed study of Rf and No isotopes radioactive decay properties

M.S. Tezekbayeva[*,1,3], A.V. Yeremin[1,2], O.N. Malyshev[1,2], M.L. Chelnokov[1], V.I. Chepigin[1], A.V. Isaev[1], A.V. Karpov[1,2], A.A. Kuznetsova[1], A.G. Popeko[1,2], Yu.A. Popov[1,2], A.I. Svirikhin[1,2], E.A. Sokol[1], A. Lopez-Martens[4], K. Hauschild[4], O. Dorvaux[5], B. Gall[5], P. Mosat[6], B.S. Sailaubekov[1,2,3]

[1]Joint Institute for Nuclear Research, Dubna, Russia

[2]State University «Dubna», Dubna, Russia

[3]Institute of Nuclear Physics, Almaty, Kazakhstan

[4]Center for Nuclear and Materials Science, IN2P3- CNRS, Orse, France

[5]Hubert Curien Multi-Disciplinary Institute, IN2P3- CNRS, Strasbourg, France

[6]Comenius University, Bratislava, Slovakia

E-mail: tezekbaeva@jinr.ru

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The experiments of detailed study of No and Rf isotopes radioactive decay properties in complete fusion reactions ^{50}Ti+ ^{208}Pb and ^{48}Ca+ ^{208,206,204}Pb with subsequent neutron evaporation from the excited compound nucleus at the kinematic separator SHELS were performed in FLNR JINR. The data of the ^{256}Rf decay properties and preliminary data of ^{250}No decay properties are presented.

Keywords: No and Rf isotopes, radioactive decay, complete fusion reactions, excited compound nucleus.

Introduction

Improvement in the experimental methods and carrying out experimental investigation with the latest developments in the detection system area are one of

the main objectives in modern nuclear physics of superheavy and heavy elements synthesis. The probability of formation is much higher for heavy isotopes than for superheavy (SHE, Z>106) that is why this region of transfermium elements ($100 \leq Z \leq 106$) is more available for studying with the recent investigation methods. Moreover, the transfermium region (neutron-rich isotopes from No to Sg) is the most interesting for spectroscopic researching on its own due to the presents transition from neutron subshell N=152 to N=162, and the cross sections of these isotopes are sufficiently high. We obtain preliminary information about what we should expect in the SHE region by means of studying heavy isotopes region.

The experiments of detailed study of isotopes radioactive decay properties of transfermium elements (α, β, γ-spectroscopy) are performed in the Laboratory of Nuclear Reactions, JINR at the recoil kinematic separator SHELS (modernized VASSILISSA) [1, 2].

Description of the experiments

In 2018-2019 years at U-400 cyclotron at FLNR, JINR experiments on detailed study radioactive decay properties of Rf and No isotopes were performed. These isotopes were produced in the complete fusion reactions of accelerated heavy ion beam of ^{50}Ti or ^{48}Ca with target nuclei of lead isotopes. In the experiments ^{208}PbS, ^{206}PbS and ^{204}PbS targets on 1.5 μ Ti substrate were used. Detailed parameters of the experiments are shown in the Table 1.

Table 1.
Conditions of experiments.

Experiment	Accelerated ion beam	Beam energy, MeV	Type of target	Target thick-ness, mg·cm^{-2}	Particles integral flux	Investigated isotope
I (2018 y.)	^{50}Ti	245	^{208}PbS	0.4-0.6	5.05·10^{18}	^{256}Rf
II (2019 y.)	^{48}Ca	224-225	^{208}PbS	0.36±0.03	8·10^{17}	^{254}No
	^{48}Ca	224-226	^{206}PbS	0.40±0.04	4.6·10^{17}	^{252}No
	^{48}Ca	224-226	^{204}PbS	0.47±0.05	2.6·10^{18}	^{250}No

The targets in the form of segments are mounted on a rotating disk in the target block of the SHELS kinematic separator in order to reduce heat load [1, 2]. The transmission eefficiency of recoils, produced in the complete fusion reactions with ions of ^{48}Ca and ^{50}Ti from the target to the focal plane of the separator, is equal to 30 - 40% depending on the settings of the separator ion-optical system.

Sophisticated detection system GABRIELA is located in the separator focal plane, allows to detect α-particles, γ-quants, β-particles and spontaneous fission fragments (SF), emitted from nuclei under the question [3, 4]. After separation from the background products our recoils, flying through the time of flight system,

which consists of 2 (start and stop) detectors,are implanted into the focal double side silicon strip detector DSSD (128 × 128 strips, size 100 × 100 mm ^{2} , thickness 0.5 mm). Additional 8 strip detectors (16 × 16 strips, size 50 × 60 mm ^{2} , thickness 0.7 mm) are mounted on the side of the focal detector, forming «well» with the depth 6 cm, are used for increasing of the detection efficiency of α - β -particles, and SF fragments, emitted from focal DSSD-detector. The energy resolution for α -particles in the range 6 - 10 MeV, which was measured in the previous experiments on the modernized separator [3], is about 15 - 20 keV. Four single crystals of germanium detectors are arranged around the «well». Clover four-crystal germanium detector is located maximum close to the focal DSSD detector [4]. The germanium detectors surrounded by BGO protection in order to reduce background influence from γ -quants.

Results

In the experiments of ^{256}Rf the SF properties studying at the SHELS separator with using neutron detector consists of ^{543}He-counters, could not be observe a single event of α -decay, corresponding to ^{256}Rf. The number of SF events related to this isotope equals to 1500 [5, 6]. In earlier experiments [7, 8], which were performed at GSI, Darmstadt, α -decay events assigned to decay of ^{256}Rf were observed. The α -decay probabilities were $b_\alpha = 0.022^{+0.073}_{-0.018}$ [7] and $b_\alpha = 0.0032$ [8].

In this experiment, decay properties of ^{256}Rf were refined in investigating the complete fusion reaction ^{50}Ti+ ^{208}Pb $\rightarrow$ ^{256}Rf*. During the experiment, in the separator focal plate it was detected about 6270 SF and nine α -decay events, which can be assigned to decay of ^{256}Rf. α -decay events were obtained as a result of recoil – α - α correlation analysis (Table 2).

Table 2.
Recoil- α - α correlation analysis for isotope decay of ^{256}Rf, E_R - recoil energy, Δ T(R- α_1) - time difference between detected mother nucleus and recoil, E_{α_1} - energy of mother nucleus, Δ T(α_1 - α_2) - time difference between mother and daughter nuclei, E_{α_2} - energy of daughter nucleus.

E_R, keV	ΔT(R-α_1), msec	E_{α_1}, keV	ΔT(α_1-α_2), sec	E_{α_2}, keV
10810	21.57	8793	2.585	8418
8148	6.79	8780	2.456	8417
9738	8.078	8789	3.703	8412
8910	0.3	8749	2.226	8417
9402	29.87	8790	6.614	8420
11540	0.134	8726	5.027	8377
9330	3.424	8781	3.369	8405
9120	9.185	8798	3.505	8415
10795	0.981	8794	1.904	8411

The measured half-lifetimes were equal to (6.9 ± 0.23) m sec for SF and (5.7 ± 1.2) m sec for α - decay, decay probabilities were b_{SF} =99.71% and b_α =0.29% respectively, which are in a good agreement with the published data [6-8]. The table 3

shows the radioactive decay properties of ^{256}Rf according to obtained and existing data.

Table 3.
The existing published data according to isotope decay of ^{256}Rf and the results of current experiment. N_α / N_{SF} -the numbers of detected α-particles/SF fragments, E_α - energy of α-particles, b_α / b_{SF} - α-decay/SF probabilities.

Exp.	α-decay				SF		
	N_α	E_α, keV	$T_{1/2}$, msec	b_α	N_{SF}	$T_{1/2}$, msec	b_{SF}
[6]	1	8812±23	10^{+47}_{-4}	$0.022^{+0.073}_{-0.018}$	73	$7.4^{+1.3}_{-0.8}$	0.978
[7]	3	8776-8800	-	0.0032	1900	6.2±0.2	0.9968
[8]	0	-	-	-	1500	5.75±0.17	≈1
2018 y.	9	8726-8798	5.7±1.2	0.0029	270	6.9±0.23	0.9971

No isotopes. Preliminary results

After two neutrons evaporation from compound nucleus the complete fusion reactions ^{48}Ca+ ^{208,206,204}Pb → ^{256,254,252}No* produces the isotopes ^{254,252,250}No. These isotopes mainly experience α-decay and SF with half-life times from few microseconds up to few seconds (Table 4).

Table 4.
The radioactive decay properties of ^{254,252,250}No [9].

	$T_{1/2}$	b_α	E_α, keV	b_{SF}
^{254}No	51 sec	0.9	8100	0.0017
^{252}No	2.44 sec	0.707	8415; 8372	0.293
^{250}No	4.2 μsec	<0.02		1

During irradiation of ^{208}PbS target with accelerated ions beam of ^{48}Ca we have detected about 600 recoil - SF fragment correlation events in the focal plane. We observed two activities, which could be assigned to SF of ^{254}No and ^{252}No. It connects with a high fission probability of ^{252}No isotope, which is produced on an impurity of ^{206}Pb in the main target. More over, the SF probability of ^{254}No is 0.17%, while for ^{252}No this value is 29.3%. These two isotopes well separate via half-life times due to the large difference between their life times. As a result, about 310 SF events were assigned to decay of ^{254}No.

At the experiment time, the gained statistic was comparable with previous experiment at GSI Darmstadt [10]. Two SF events with short life times, which could be preliminary assigned to decay of ^{254}No isomeric state, were observed. There were γ-quants (E_γ =159 keV), are emitted by ^{254}No nucleus via the transition from 6+ to 4+ level.

During ^{206}PbS target irradiation with accelerated heavy ion beam of ^{48}Ca in the focal plane about 2200 SF events were detected, assigned to decay of ^{252}No.

The obtained statistic was enough for detectors calibration via total kinetic energy (TKE). We have also observed γ-quants (E_γ =167 keV), which are emitted from ^{252}No nucleus via the transition from 6+ to 4+ level.

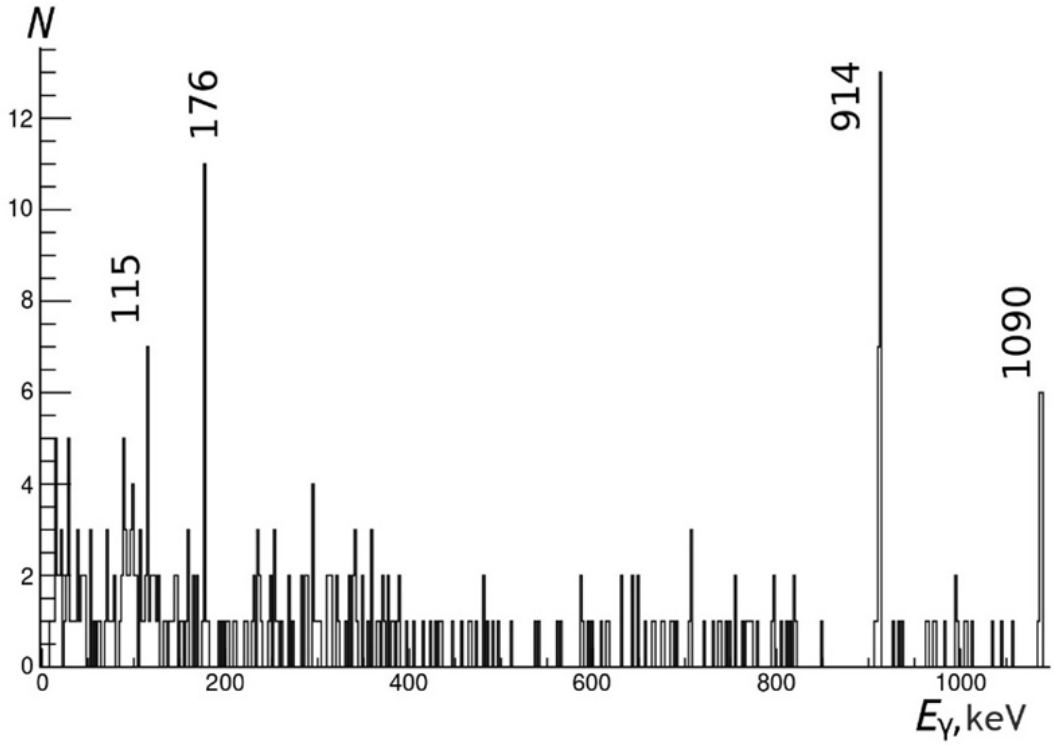

Figure 1. Spectrum of detected γ-quants from the decay of ^{250}No. E_γ - γ-quants energy. N-counts.

The final stage of experiment with ^{48}Ca beam was studying decay properties of ^{250}No, which is synthesized in $2n$ channel of the complete fusion reaction $^{48}\text{Ca}+^{204}\text{Pb} \rightarrow {}^{252}\text{No}^{*} \rightarrow {}^{250}\text{No}+2n$. Totally, in the focal detector (DSSD) in 13 days of ^{204}PbS target irradiation about 19000 recoil – SF fragment correlation events were detected. At the Figure 1 spectrum of γ-quants is given, 914 keV and 1090 keV are visible, and difference between them is equal to 176 keV. This peak with energy 176 keV is also observed in the spectrum. Lines 115 and 176 keV in well agreement with expected out come in the rotational band of ground state based on known data of ^{254}No and ^{252}No ground state bands (Figure 2a and Figure 2b respectively).

For these No isotopes the transition from 6+ level to 4+ occurs from 159 keV in ^{254}No to 167 keV in ^{252}No, the transition from 4+ to 2+ occurs with photons emission with energy 101 and 107 keV and from 2+ to 0+ with 44 and 46 keV respectively [9]. Based on these data we can imagine decay scheme of ^{250}No, is shown at Figure 2c. Decay from 6+ isomeric state is accompanied by transitions 914 keV with multipolarity M1 in 6+ and 1090 keV with multipolarity with E2 in 4+ of ground state. The transition from 6+ to 4+ is 176 keV, from 4+ to 2+ is 115 keV and from 2+ to 0+ $\approx$ 49 keV.

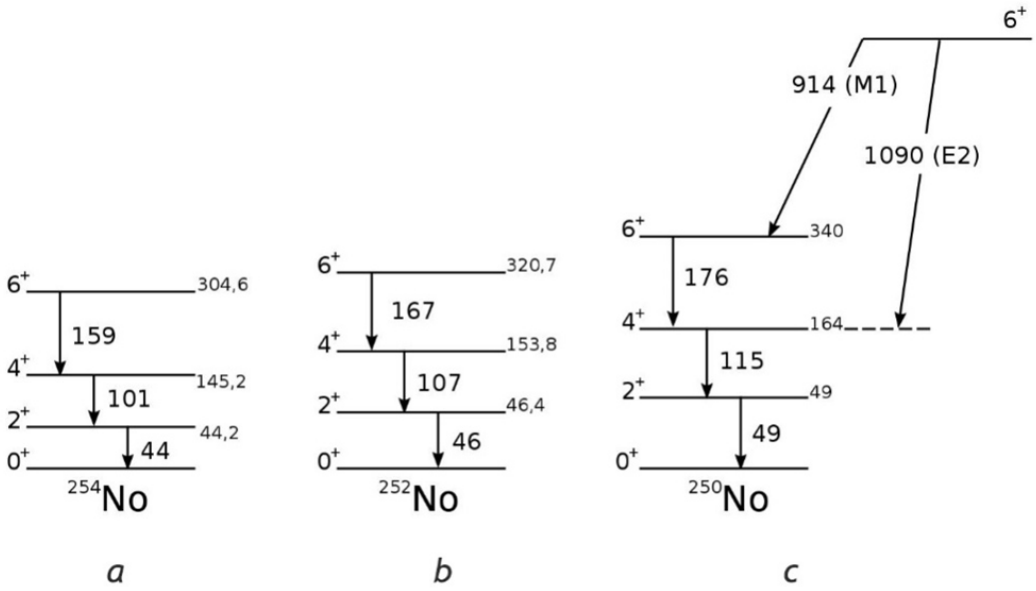

Figure 2. a) Rotational band of ^{254} No ground state; b) Rotational band of ^{252} No ground state; c) Presumed decays scheme of ^{250} No, based on obtained data from the experiment and existing data of ^{254} No and ^{252} No.

Conclusion

The preliminary results of ^{250} No isomer state studying were presented and some decay properties of ^{256} Rf were refined in this paper with α, β, γ-spectroscopy technique successfully implemented at the kinematic separator SHELS. In spring 2019, the first launch of SHE factory was held at JINR. The data analysis presented in this work based on the used investigation methods, will allow us to study in detail the structure of transfermium elements. We expect be amintensity on the new cyclotron DC-280 approximately 10 times more than we have now at the working U-400 cyclotron. It is planned top roduce heavy ion beams with intensity up to 10 p μA at the SHE factory, FLNR, JINR [11]. The using of such high-intensity beams in combination with effective methods and experimental facilities should open up access to the study of nuclei closer to the center of the "Island of stability".

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