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Spectroscopy of transfermium elements at Dubna: results and plans

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During the last 12 years using the GABRIELA (Gamma Alpha Beta Recoil Invetsigations with the ELectromagnetic Analyser) detector set-up and kinematic recoil separators VASSILISSA / SHELS the experiments aimed to the gamma and electron spectroscopy of the Fm – Db isotopes, formed at the complete fusion reactions ^{48}Ca $+^{207,208}$Pb $\rightarrow^{255,256}$No*, ^{48}Ca $+^{209}$Bi $\rightarrow^{257}$Lr*, ^{22}Ne $+^{238}$U $\rightarrow^{260}$No*, ^{50}Ti $+^{208}$Pb $\rightarrow^{258}$Rf* and ^{50}Ti $+^{209}$Bi $\rightarrow^{259}$Db*, were performed at FLNR JINR.

Keywords: transfermium nuclei, alpha – gamma spectroscopy, cross-sections.

Introduction

In the past, various types of reactions and identification techniques were applied in the investigation of formation cross sections and decay properties of transuranium elements. The fusion - evaporation reactions with heavy targets, recoil - separation techniques and identification of nuclei by the parent-daughter generic coincidences with the known daughter-nuclei after implantation into position - sensitive detectors were the most successful tools for production, identification and detailed study of decay properties of the isotopes of heaviest elements known presently.

With $\alpha-$, $\gamma-$ and $\beta-$ detectors array, so-called GABRIELA detector system [1], installed at the focal plane of the VASSILISSA separator [2], detailed spectroscopy of neutron deficient Fm – Db isotopes (using ^{48}Ca and ^{50}Ti accelerated ions) was performed during last 12 years.

A synthesis of neutron rich transfermium isotopes in complete fusion reactions is only possible when asymmetric combinations of incident ion and target nucleus are used. In this case, projectile ions similar to ^{18}O and ^{22}Ne are mostly used in combination with targets of uranium and transuranium isotopes. Production cross sections of evaporation resudes(ER) in such reactions are rather high (hundreds of pbarn to tens of nbarn) [3], but their charge, angular, and energy distributions are very wide due to their small velocity after escaping from the target [4]. Experimental experience allowed us to perform ion optical calculations and to design the new experimental set up, which will collect the base and best parameters of the existing separators and complex detector systems used at the focal planes of these installations. New experimental set up (SHELS, the velocity filter) on the basis of existing VASSILISSA separator was developed for synthesis and studies of the decay properties of heavy nuclei [5,6,7]. The average ER transmission efficiency increased twofold for asymmetric combinations with incident ^{22}Ne ions. The second stage of modernization of the experimental installation included the improvement of the detector system of the separator.

During the experimental campaign of year 2014 the new double sided silicon detector (DSSD) was used at the focal plane of the SHELS separator strips (128x128, 100x100 mm^2). The detector demonstrated high stability and ensured a high resolution (0.2%) of alpha particle registration.

The final version of the new detector set-up was completed in the first half of 2015. It will consist of a $10 \times 10cm^2$ DSSD focal-plane stop detector surrounded by eight $5 \times 6cm^2$ silicon tunnel detectors (0.7 mm thick) in the backward hemisphere. The modernized GABRIELA set up consisted of 1 Clover detector, placed just behind the DSSD focal-plane stop detector and 4 single crystal Gammasphere Phase I type Ge detectors surrounding the new vacuum chamber of the focal plane stop-detector (see Figure 1). The experimental tests showed that detection efficiency for gamma quanta for new set up was increased by factor of 3 in comparison with old GABRIELA system [1].

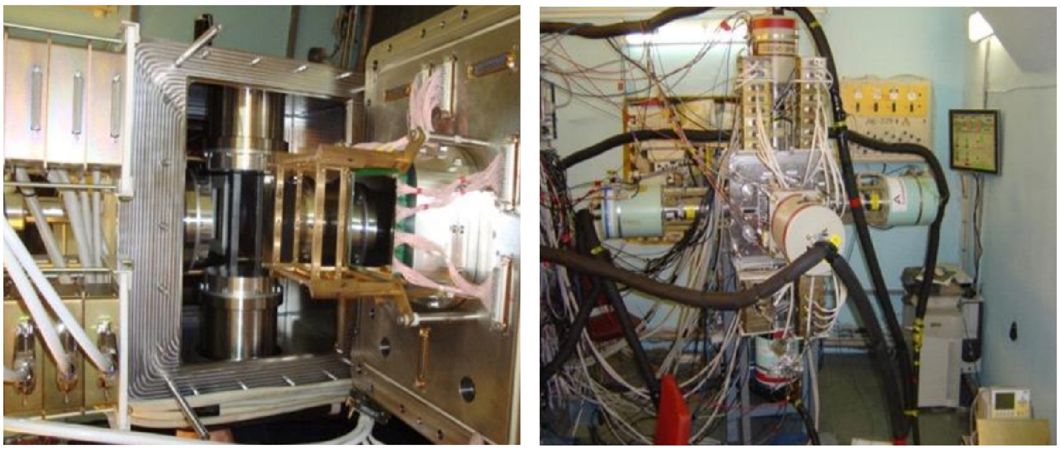

Figure 1. Left panel: Large area DSSD focal plane detector. Right panel: combination of 4 single crystal Ge detectors and one Clover Ge detector (at the back side of the detector chamber).

Experiment and Results

A detailed study of the heavy ion reaction mechanisms resulting in superheavy nuclei and measurement of their decay properties, half-lives, decay energies and decay modes, are the basic motivations of our common work. Because reaction studies cannot be performed systematically on a cross-section level of picobarns and below, which is the case for synthesis of the heaviest elements, we investigate especially for reaction and spectroscopy studies projectile-target combinations having cross-sections of microbarns down several tens of picobarns. This is the case for synthesis of elements in the region from Fermium to Darmstadtium. In Figure 2 summary of the results of experiments aimed to the detailed study of decay properties of (Fm – Db)–isotopes obtained with the use of VASSILISSA/SHELS separator is presented. The latest result, obtained at year 2016, was spectroscopy study of the decay of ^{257}Db isotope, synthesized in the complete fusion reaction $(^{50}\mathrm{Ti} + ^{209}\mathrm{Bi}) \rightarrow (^{259}\mathrm{Db} + 2n)$.

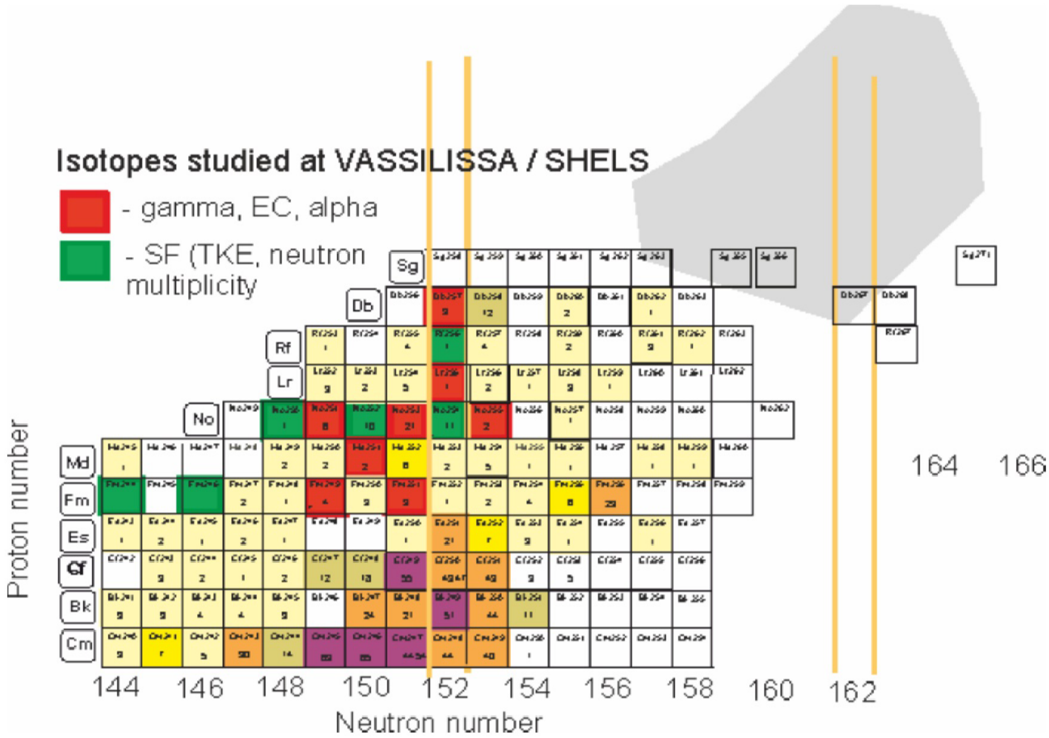

Figure 2. Summary of the experimental results obtained with the use of VASSILISSA /SHELS separator.

The experimental results for the isotopes in Fm–Lr region were published previously, see works [8-11] and references therein. Experiments aimed to the study of spontaneous fission of short lived transfermium isotopes are described in details in the work [12]. The list of experiments performed using SHELS separator in year 2016 is presented at Table 1.

At the beginning of year 2016 we performed experiment, aimed to the spec-troscopy studies of the ^{255}Lr, synthesized in the complete fusion reaction $^{48}\mathrm{Ca}(^{209}\mathrm{Bi}, 2n)^{255}\mathrm{Lr}$. Modernized recoil separator (SHELS) and new detector chamber together with Clover and 4 Ge single crystal gamma detectors were used at the experiment (see Figure 1). The experiment showed that that modernization of ion optical system of the separator together with increase of the gamma detection efficiency by at least factor of 3 for new design of detector system resulted in the increase of statistics collected for the same integral flux of incident ions by factor of 10 (see Figure 3).

Table 1.
The list of experiments performed using SHELS separator in year 2016.

Reaction	Goal	Experimental results
15 January – 01 February 2016		
$^{48}Ca(^{209}Bi, 2n)^{255}Lr$	Collecting of statistics for ^{255}Lr	Efficiency of experiment increase by 10 times
16 May– 21 June 2016		
$^{50}Ti(^{209}Bi, 2n)^{257}Db$	Collecting of statistics for ^{257}Db	About 1000 events of ^{257}Db, measured cross section for p0n channel $\sim$ 10 pb
21 – 28 June 2016		
$^{50}Ti(^{209}Bi, 3n)^{256}Db$	Search for p1n channel	Cross section limit for p1n channel $\sim$ 10 pb
20 October – 16 November 2016		
$^{50}Ti(^{209}Bi, 2n)^{257}Db$ $^{50}Ti(^{209}Bi, p2n)^{256}Rf$	Collecting of statistics for ^{257}Db. Search for p2n channel	Data is under analysis

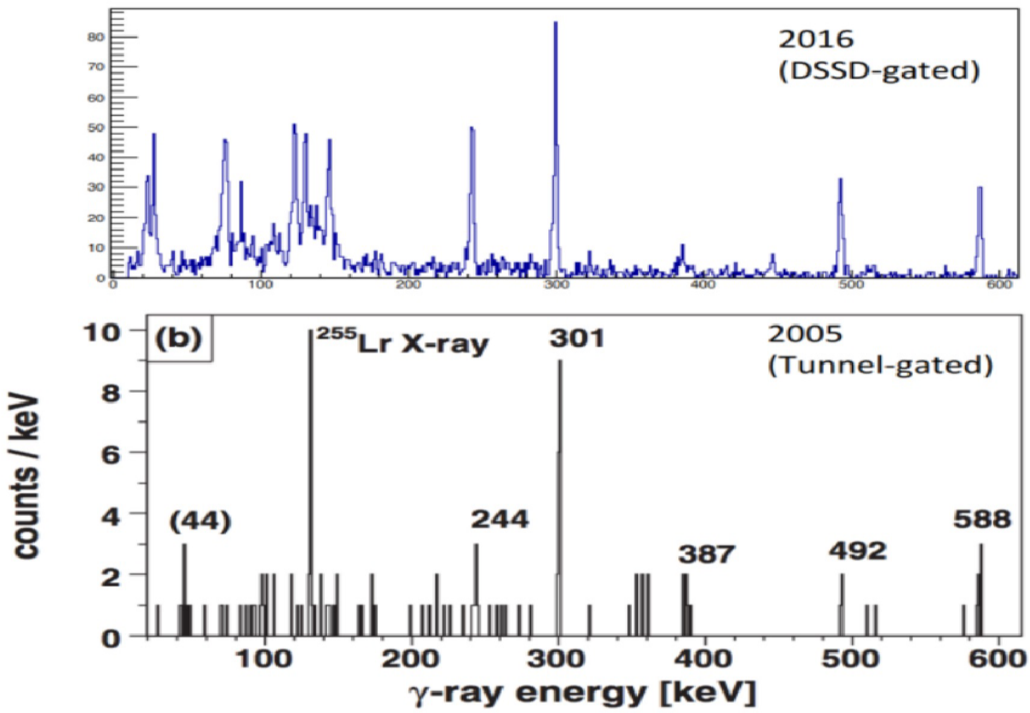

Figure 3. Number of gamma decays collected for the same ingeral flux $(1.4 \times 10^{18} / ^{48}Ca$ ions$)$ in the case of old separator(year 2005, bottom panel) and modernized separator together with new detector system (year 2016, top panel).

The goal of main experimental campaign in the year 2016 was spectroscopy study of the isotope ^{257}Db, synthesized in the complete fusion reaction $^{50}Ti(^{209}Bi, 2n)^{257}Db$. The collection of statistics was performed during 2 experimental runs, see Table 1. The number of detected decays of ^{257}Db exceeds 1000 events, some correlated decays are presented at Figure 4. These experiments were the continuation of our studies of the decay of N = 152 isotope ^{255}Lr [8]. Another important part of our experimental program for the year 2016 was search for the exotic deexcitation channels of evaporation residues with evaporation of proton and few neutrons. Theoretical calculations predicted formation cross sections for the synthesis of transfermium isotopes via pxn channels factor of (10 – 100) lower than for xn – channels . The only experimental result for formation cross sections of ^{256}Md isotope, synthesized via reaction $^{22}Ne(^{238}U, p3n)^{256}Md$, was obtained many years ago [13] and need additional tests. The interest for the investigations of evaporation residue formation via channels with evaporation of proton and few neutrons is in the possibility for synthesis of more neutron rich transfermium isotopes than via xn channels in the case of some target – projectile combinations. In the Figure 5 some experimental results for pxn channels, obtained with the use of SHELS and GABRIELA in year 2016, together with theoretical calculations are presented.

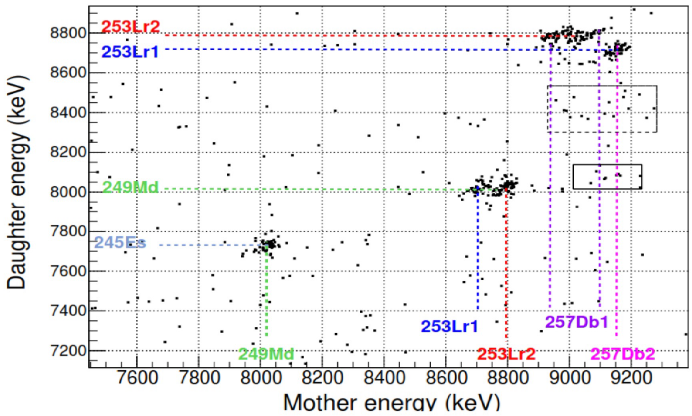

Figure 4. Correlated decays $^{257}Db \rightarrow ^{253}Lr \rightarrow ^{249}Md$, detected in the experiments with SHELS and GABRIELA in year 2016.

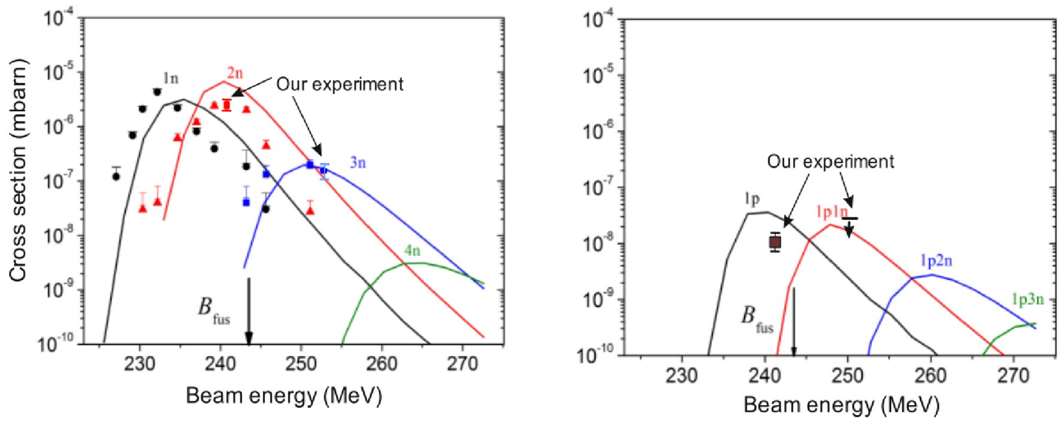

Figure 5. Left panel: Existing experimental data for synthesis of Db isotopes in complete fusion reaction $^{50}Ti + ^{209}Bi \rightarrow ^{259-x}Db$ + xn (symbols) from [14]. Colour lines – theoretical calculations. Right panel: Our experimental results in the year 2016 (symbols). Data for p2n channel is under analysis. Colour lines – theoretical calculations.

Conclusion

The experiments performed on the SHELS separator and modernized GABRIELA detector set up showed the sufficiently increased experimental efficiency. This factor allowed us to perform experiments aimed to the spectroscopy studies of ^{257}Db isotope, synthesized in the complete fusion reaction

$(^{50}\text{Ti} +^{209} \text{Bi}) \rightarrow (^{257}\text{Db} + 2n)$ with formation cross section at the maximum of excitation function about 2 nbarn [14]. In the close future we plan to continue our experiments with accelerated ^{50}Ti beam in order to perform spectroscopy investigations of decay properties of even – odd Rf isotopes and detailed study of the spontaneous fission properties of even – even Rf isotopes. Next step to the heavier isotopes will be provided with the use of ^{54}Cr accelerated beams for spectroscopy studies of the decay of Sg isotopes.

Acknowledgments

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