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MODERNIZATION OF THE DETECTOR SYSTEM AT THE RECOIL SEPARATOR VASSILISSA

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Модернизация детектирующей системы сепаратора ядер отдачи ВАСИЛИСА

Последние десять лет сепаратор ядер отдачи ВАСИЛИСА использовался для изучения ядер — остатков испарения, образующихся в реакциях полного слияния с тяжелыми ускоренными ионами. В рамках экспериментальных работ в области элементов с $92 \leq Z \leq 94$ четырнадцать новых изотопов были идентифицированы с использованием корреляционной (материнское — дочернее ядро) методики.

Для планируемых экспериментов по синтезу новых изотопов сверхтяжелых элементов ($Z \geq 110$) с использованием интенсивных выведенных пучков ^{48}Ca была проведена модернизация детектирующей системы, расположенной в фокальной плоскости сепаратора. В результате энергетическое и позиционное разрешение детекторов было существенно улучшено, эффективность регистрации α-частиц увеличена до 85 %. Были исследованы свойства радиоактивного распада нового изотопа 112 элемента и синтезирован изотоп нового 114 элемента с массовым номером 287. В обоих случаях наблюдалось два события распада искомых ядер.

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Modernization of the Detector System at the Recoil Separator VASSILISSA

Within the past ten years, the recoil separator VASSILISSA has been used for the investigations of evaporation residues produced in heavy ion induced complete fusion reactions. In the course of experimental work in the region of the elements with $92 \leq Z \leq 94$, fourteen new isotopes have been identified by the parent — daughter correlations.

For further experiments aimed at the synthesis of the superheavy element isotopes ($Z \geq 110$) with intensive ^{48}Ca extracted beams, improvements in the focal plane detector system have been made. As a result, energy and position resolutions of the detectors have been significantly improved, the detection efficiency for the α-particles, emitted from the implanted into the focal plane detector recoil nuclei, has been increased to 85 %. The decay properties of the new isotope of element 112 and the isotope of the new element 114 with mass 287 have been measured in two-nuclei decays.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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1 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 and identification of the heaviest elements known presently. This technique may be further improved and presently it may be very promising for the identification of new elements, search for new isotopes and measurement of new decay data for the known nuclei.

At the Flerov Laboratory of Nuclear Reactions (JINR, Dubna), investigations of the complete fusion reactions leading to the synthesis of superheavy nuclei with the use of heavy ion beams from a powerful U–400 cyclotron have been an important part of the experimental program.

The stability of heavy nuclei strongly depends on the shell structure effects. These stabilizing effects increase significantly at closed proton and neutron shells. Beyond uranium, the stability of nuclei diminishes rapidly with increasing the element number Z. According to the macroscopic–microscopic theory, the next spherical shell closure for the neutrons beyond $N = 126$ is predicted at $N = 184$. The stability of the superheavy nuclei could increase sharply, when their neutron number approaches this spherical shell closure [1, 2]. Due to the spherical ground-state and high ground-state shell-correction energy, the fission barrier is wider and higher than that for deformed nuclei, which is the reason for the expected increased stability to spontaneous fission (SF). Selection of reaction partners with the highest possible number of neutrons is essential for the synthesis of spherical superheavy nuclides and allows approaching the shell $N = 184$ as close as possible [3].

Among all target - projectile combinations available at present, complete fusion reactions induced by ^{48}Ca ions on the heavy actinide targets, such as ^{232}Th, ^{238}U, ^{242,244}Pu and ^{248}Cm, provide the most close approach to the neutron number expected for the spherical superheavy elements.

The key problem in the production of intense ion beams of the rare and extremely expensive ^{48}Ca isotope was solved after the installation of a new injection system and the modified beam optics at the U–400 cyclotron. It allowed obtaining an internal beam of $^{48}Ca^{5+}$ ions with intensities of up to 3 pμA at the material consumption rate of about 0.3 mg/h [4].

On the basis of the achieved progress with the acceleration technique, the use of intense ^{48}Ca beams became the main feature of the program of the superheavy element synthesis.

The extrapolations from the known formation cross sections of the elements with $Z \leq 112$ demonstrate the feasibility of experiments aimed at the production and investigation of the superheavy elements using ^{48}Ca beams. $^{48}Ca + {}^{238}U \rightarrow {}^{286}112^*$, $^{48}Ca + {}^{242,244}Pu \rightarrow {}^{290,292}114^*$ appear to be the best reactions from the point of view of their cross sections. For the last – mentioned reactions the extrapolation yields the cross section values from 1 to 10 pb for the 3n and from 0.2 to 1 pb for the 4n reaction channels.

For the neutron-rich nuclides with Z = 110, 112 and 114 (N = 166-167, 170-171 and 174-175, respectively), the theory [1, 2] predicts a strong increase of more than 5 orders of the magnitude in the half-lives to α and SF decay in comparison with known neutron-deficient isotopes of elements 110 - 112 [5]. Typical half-lives of the investigated isotopes could be from seconds to thousands of seconds. These facts (low cross sections and long half-lives) strongly raise the requirements for the beam quality and background conditions while using the recoil separators.

The required high sensitivity and selectivity for these experiments could be achieved due to:

1. A stable, high intensity and good quality beam of the U–400 cyclotron [4].

2. High-efficient separation of the reaction products by the recoil separator VASSILISSA [6, 7].

3. A sensitive detector system allowing the feasibility of correlation of detector implanted products to their succeeding radioactive decay chains.

The improvements of the detector module of the separator VASSILISSA which make it possible to identify new super heavy nuclei and to study their radioactive decays at the cross section level of 0.5 – 1 pb and possible half lives from 1 to 1000 seconds are described in the present work.

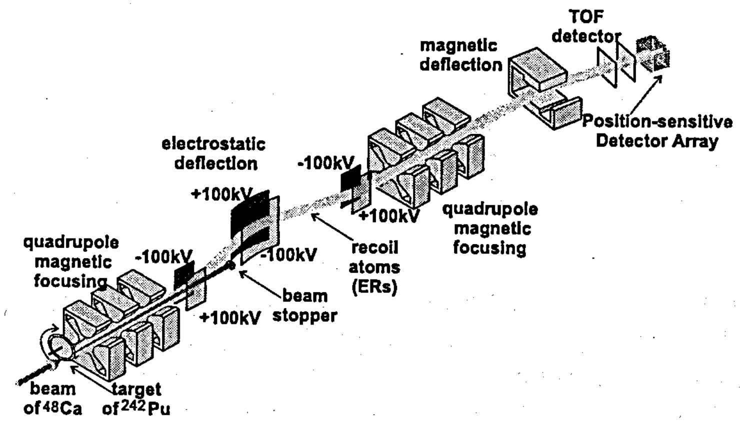

Figure 1: The schematic view of the separator VASSILISSA.

2 Experimental methods

2.1 The separator VASSILISSA

The recoil separator VASSILISSA was installed in 1987 on a beam of the U–400 heavy ion cyclotron of the FLNR JINR and since then was used in experiments. A schematic view of the experimental set-up is shown in fig. 1.

The principal component of the VASSILISSA facility is a system consisting of three electrostatic dipoles, which accomplish the spatial separation of the trajectories of recoil nuclei, multinucleon transfer reaction products and beam particles by virtue of differences in their energy and ionic charges.

Recoil nuclei (ER's) are deflected by 8^o in the first dipole to enter the second dipole aperture whereas the full energy projectiles pass through the first dipole almost unperturbed and then are stopped in the Faraday cup. Further separation of recoil nuclei from scattered projectiles and other background particles takes place in the second and third dipoles. Electric rigidity is the same for three dipoles.

Recoil nuclei emerging from the target are accepted by the separator within a solid angle of 15 msr ($\approx \pm 4^o$ in the vertical and horizontal directions). VASSILISSA tolerates the energy and charge deviations of up to $\pm$15%. A thin carbon foil of about 30 μg/cm^2, situated 8 cm behind the target, is used for ionic charge equilibration of the fusion products. The transmission properties of the separator result in optimal target thicknesses of 150 to 500 μg/cm^2. Measured in test experiments [6] and calculated [8, 9] transmission efficiencies for the ER's produced in the reactions with heavy ions ranging from ^{16}O to ^{48}Ca are from 3 to 40 % for the xn evaporation channels. The suppression factors of $> 10^{19}$ for the full energy beam particles and of $> 10^4$ for multinucleon transfer reaction products were achieved [6].

An additional dipole magnet installed behind the separator provides an 8^o deflection for the ER's and gives an additional background suppression by the factor of 10 – 50 for the scattered beam projectiles. All parameters of the experimental set–up (high voltages and magnetic fields at the quadrupoles and the dipole magnet) are controlled and operated by a computer with the use of a specially designed interface [10].

The control system allows operation of the separator elements with an accuracy of 10^{-3} and to make a protocol of the experiment. Also this system provides the beam intensity and integral flux measurements; the beam energy and the quality of the target are controlled by two silicon surface barrier detectors which measure the elastically scattered projectiles from a thin (200 μg/cm^2) gold foil and the target, respectively (see fig. 1).

To avoid the damage of the Au - foil it was necessary to decrease the beam intensity to 0.5 eμA during the beam energy measurements. For providing a continuous and uninterrupted beam energy monitoring of high intensity beams we installed two pick-up electrodes into the beam line. The distance between the electrodes is 10.24 m. In the recent experiments, the continuous beam energy monitoring was performed with the use of the time-of-flight system. The accuracy was about 0.3 %.

2.2 Focal plane detector system

The detector system consisting of two (start and stop) time–of–flight detectors [11] and an array of silicon detectors have been developed and installed in the separator focal plane. Thin plastic foils (30–70 μg/cm^2 in thickness, 80 mm in diameter) emitting secondary electrons and microchannel plates for detecting these electrons are used in the both time–of–flight detectors. The typical time resolution of about 0.5 ns was obtained for slow (total energy of 10–20 MeV) recoil nuclei having mass numbers of about 200. The value of 99.95% was achieved for the probability of detection of such recoil nuclei by making use of a single timing detector.

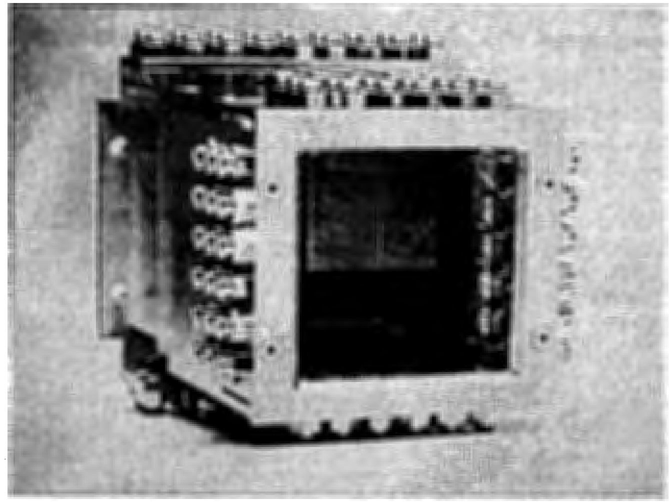

Figure 2: The view of the focal plane detector array.

Having passed the time–of–flight detectors, the recoil nuclei are implanted into the silicon detectors. In order to improve the sensitivity of the experimental set-up, a new detector array has been manufactured and installed at the focal plane of the separator for the experiments aimed at the synthesis of heavy (Z $\geq$ 108) elements with the use of ^{48}Ca bombarding ions. The detector array consists of five identical 16 – strip silicon wafers (see fig. 2.).[2]

The active area of a single silicon strip detector is 60×60 mm^2. As for the stop detector, its every strip is position sensitive in the vertical direction with a resolution of 0.3 – 0.5 mm between α decays of the α decay chain. The average energy resolution is 20 keV for α's of the ^{241}Am source. Four wafers are mounted in the backward hemisphere facing the stop detector. They measure escaping α's or fission fragments, and the total geometrical efficiency is 85 % of 4 π. In case of the backward detectors, the strips do not have any position resolution and each four neighboring strips are connected galvanically so that 16 energy sensitive segments are formed.

The measurement of the time–of–flight and energy of the ER's yields their mass values with an accuracy of about 10% thus allowing separation of ER's from the target–like and beam–like particles using two–dimensional

[2]The R&D of the detectors and the housing were performed by the Canberra Semiconductor NV.

TOF–Energy spectra. The anticoincidence condition for the signals from the time–of–flight and silicon detectors is used to distinguish between the pulses originating from the ER's and their α-decays, i.e. to obtain the "clean" α-spectra of the recoil nuclei implanted into the silicon detectors.

To reduce the low-energy background of the scattered projectiles and to shift their energy distribution to lower energies (less then the range of 6–9 MeV characteristic of α–decay) a 200 – 400 $\mu g/cm^2$ thick mylar degrader foil has been inserted in front of the silicon detector array.

2.3 Electronic and data acquisition systems

Altogether up to 44 parameters were measured for each event. Energies and positions were recorded with two different amplifications: the first one of up to 300 MeV to measure fission energies and the other one of up to 20 MeV for ER's and α particles. The spectroscopy amplifiers had been designed and manufactured at the Flerov Laboratory. They demonstrated an excellent stability resulting in the deviation of the α peak position of $\pm$ 0.05 % during a month of operation at room temperature fluctuations of $\pm$ 5 C^o.

All the analog signals were coming to 8–channel multiplexers and after that converted in 4096 channel ADC's (80 μs is the conversion time for the total range). In order to have an opportunity of recording the following fast α decays ($T_\alpha \leq 80$ μs), an alternative ADC was used. When one of the principal ADC_α was engaged in the conversion of the amplitude of the α event signal, the alternative ADC was ready to accept the analog signal. Thus, the data of the second α event which would fail into the dead time of the first event were not lost, but stored as a second event at the alternative ADC. Each ADC was combined with a 32 bit scaler having an accuracy of 1 μs. The time differences between the following each other particles of the decay chain were measured within a coincidence time of 1 μs.

The data acquisition system of VASSILISSA allows storing, event by event, information concerning the energy, position, time–of–flight and arrival time of the recoil nuclei implanted into the focal plane detector, as well as the position, detection time and energy of the recorded alpha decay and spontaneous fission events in the detectors. Some additional parameters were also recorded together with the codes of the events. At present, the length of the event word is 88 bytes.

A specially developed interface is used to transfer the data from CAMAC crates to the memory of the PC AMD-586-133 working under DOS 6.22 and Windows Networks. This PC collects and filters the events and sends them to LAN. The front-end PC is linked via a 100 Mbit fast ETHERNET cable to a PC AMD-486-100 running under Windows 95, which supervises the system and stores the data. The distance between the PC's is 60 meters.

All the data are stored in a reference list mode on a 9 Gbyte hard disk. It is controlled by specially developed software [12], which provides the complete on–line analysis of the data excluding the correlation analysis. Also it provides the control of high voltage on time–of–flight and semiconductor detectors. The off–line analysis is performed with the Alpha station 200 computer using the program system GOOSY [13].

3 Results

3.1 Test experiments

To test the new detector system together with electronic and data acquisition systems we performed a number of test experiments. The fist experiment within this program was the study of the reaction $^{48}Ca + ^{174}Yb \rightarrow ^{222}Th^*$. The formation cross sections of the reaction products, formed via xn - evaporation channels, are rather high which allows us to collect good statistics. The reaction products and their daughter nuclides have the half lives from microseconds to hours and α decay energies from 6 to higher than 9 MeV. The energy and position resolution for the generic ER – α – α chains could be accurately tested for the new detector system.

In fig. 3 an example of the recorded α spectrum at the focal plane detector for the reaction $^{48}Ca + ^{174}Yb \rightarrow ^{222}Th^*$ at a beam energy of 220 MeV ($E^*_{CN} \approx 54$ MeV) is presented. The energy resolution of about 20 keV is clearly seen. In the case of backward detectors, we obtained the energy resolution of about 150 keV. The reason is that escaping α's hit the backward detectors over a wide range of angles.

An example of the recorded α spectrum at the backward detectors for the same reaction and beam energy is presented in fig. 4.

To determine the position resolution for the $ER \xrightarrow{E_{ER},t_{ER}} \alpha_1 \xrightarrow{E_{\alpha_1},t_1}$ correlations the evaporation residues $^{216,217}Th$, formed after the evaporation of 5

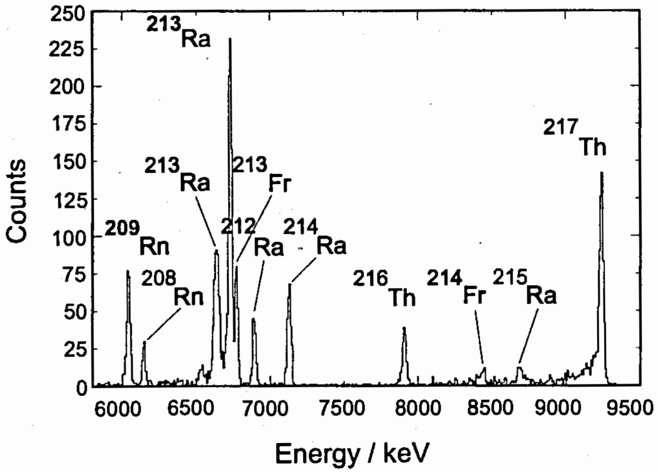

Figure 3: An example of the recordered α spectrum at the focal plane detector for the reaction $^{48}Ca + {}^{174}Yb \rightarrow {}^{222}Th^*$ at a beam energy of 220 MeV ($E^*_{CN} \approx 54$ MeV)

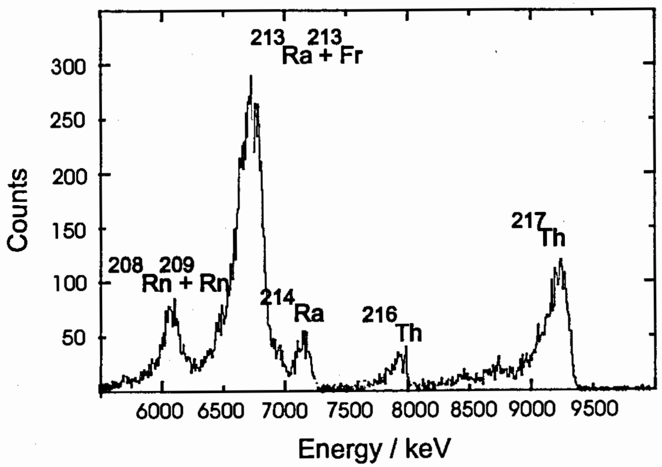

Figure 4: An example of the recordered α spectrum at the backward detectors for the reaction $^{48}Ca + {}^{174}Yb \rightarrow {}^{222}Th^*$ at a beam energy of 220 MeV ($E^*_{CN} \approx 54$ MeV).

and 6 neutrons respectively, were used. For ER - α correlations the position resolution Δx of about 0.8 mm was obtained. The relative position distribution of the correlated α particles from ER's is presented in fig. 5-

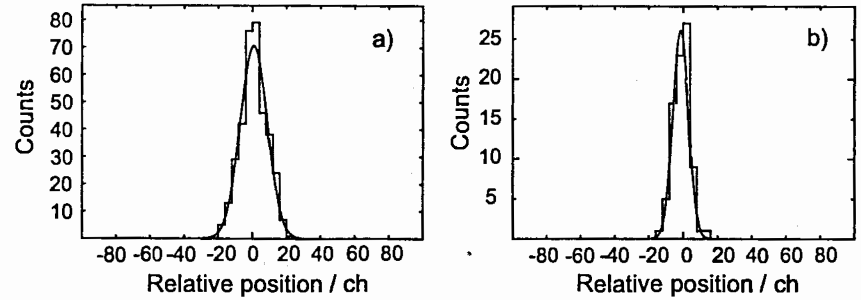

Figure 5: **a)** – a relative position distribution of the correlated α particles with the $^{216,217}Th$ ER's, formed after the evaporation of 5 and 6 neutrons, respectively; **b)** – a relative position distribution of the correlated α particles for the correlations $^{216,217}Th \rightarrow {}^{212,213}Ra$. One channel is equal to 0.06 mm. Smooth solid line shows the Gaussian fit of the peak.

a (1 channel in our case corresponds to 0.06 mm). For the correlations $^{216,217}Th \rightarrow {}^{212,213}Ra$ the result was even better and the value of $\Delta x = 0.5$ mm was obtained (see fig. 5-b).

In the region of the new neutron rich isotopes of superheavy elements, which we plan to investigate with the use of a ^{48}Ca beam, the spontaneous fission (SF) of those isotopes or their descendants is very much likely. To test our detector system for the case of the ER – SF correlations and to calibrate SF energy spectra we studied the reaction $^{48}Ca(^{206}Pb,2n)^{252}No$. The detected α energy spectrum is presented in fig. 6.

The corresponding relative position spectra for the ER – α and α – α ($^{252}No \rightarrow {}^{248}Fm$) spectra are presented in fig. 7.

The position resolutions Δx of about 0.8 mm for the first case and of 0.6 mm for the second case were obtained. We collected good statistics for the SF events from ^{252}No which allows us to calibrate the SF energy spectra using data from [14] (see fig. 8-a). The position resolution Δx of about 1.0 mm was obtained for the ER – SF correlations (see fig. 8-b).

3.2 New isotopes of superheavy elements

In the course of all the test experiments, the separator itself and its detection system demonstrated the high performance stability, high quality of rejection of all unwanted reaction products, very clean detected spectra and the high energy and position resolution. The obtained results allowed

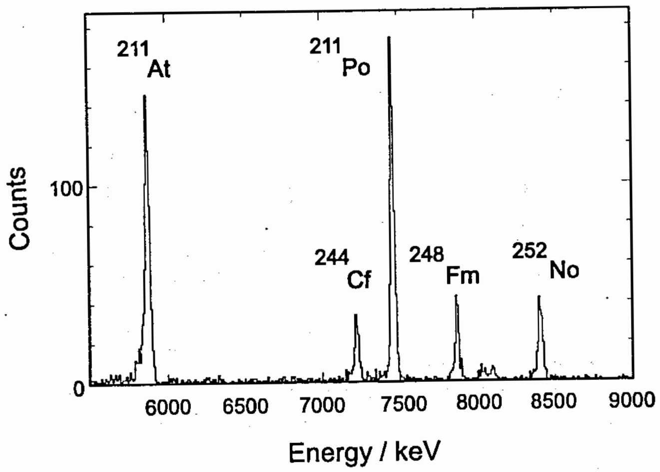

Figure 6: The detected α energy spectrum for the reaction $^{48}Ca + ^{206}Pb \rightarrow ^{254}No^*$ at a beam energy of 215 MeV ($E^*_{CN} \approx 22$ MeV).

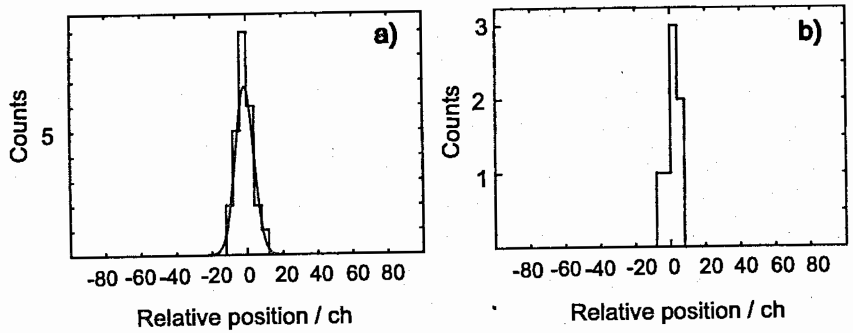

Figure 7: A relative position spectra **a)** – for the ER – α (^{252}No) correlations and **b)** – for the α – α ($^{252}No \rightarrow ^{248}Fm$) correlations. Smooth solid line shows the Gaussian fit of the peak.

us to perform a number of search experiments aiming at synthesizing the new neutron rich isotopes of elements 112 and 114 in the reactions between ^{48}Ca and ^{238}U, ^{242}Pu targets.

During the experiments the average intensity of the ^{48}Ca beam on the separator's targets was 2.5 – 4 $\times$ 10^{12} pps. The counting rate of all background events at the focal plane detector was only 25–30 Hz. At one detector's strip, the counting rate for α–like events (background without

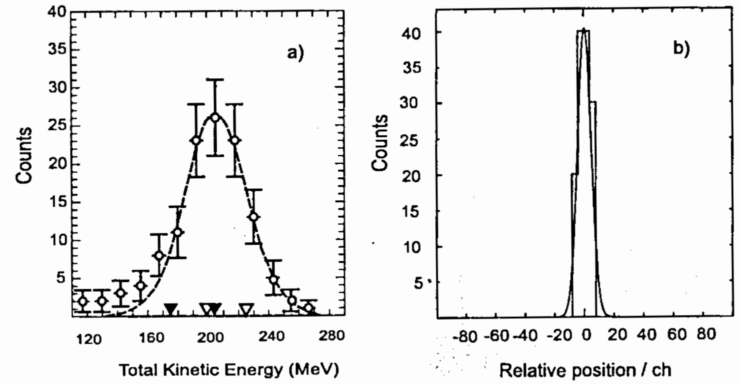

Figure 8: **a)** – The TKE spectrum for the SF of ^{252}No measured at VASSILISSA using the reaction $^{206}Pb(^{48}Ca,2n)^{252}No$. The dashed line is a Gaussian curve fitted to the data. The error bars represent statistical uncertainties only. The energy calibration was made using the results of Ref. [14]. The energies of the two fission events observed during the $^{48}Ca + ^{238}U$ irradiation are marked by the open triangles; the same for reaction $^{48}Ca + ^{242}Pu$ are marked by filled triangles. **b)** – A relative position spectra for the ER – SF (^{252}No) correlations.

a TOF signal) with energies of more than 7.5 MeV was 20–30 per hour, and for recoil–like events (background with a TOF signal) with energies of more than 4 MeV it was 80–120 per hour. Basing on the results of the test reactions, we estimated an energy range from 4 to 15 MeV for the signals originating from the implanted Z = 112 or 114 nuclei (see fig. 9).

In the case of the reaction $^{48}Ca + ^{238}U$, the experiments were performed at two beam energies resulting in excitation energies of 33 and 39 MeV. The collected beam doses were 3.5×10^{18} and 2.2×10^{18}, respectively. Two spontaneous fission events were observed at the lower beam energy, which were tentatively assigned to the new neutron rich isotope $^{283}112$ produced by the reaction $^{238}U(^{48}Ca,3n)^{283}112$ [15] (see fig. 10). The measured cross-section was ($5.0\ ^{+6.3}_{-3.2}$) pb and the half–life was about 100 s. No event was observed at the higher beam energy resulting in an upper cross–section limit of 7 pb for the 4n evaporation channel [15].

The reaction $^{48}Ca+^{242}Pu$ was investigated with the aim to synthesize an isotope of the new heaviest element Z=114. The experiment was performed at a beam energy resulting in an excitation energy of the compound nucleus of 33.5 MeV. For the collected beam dose of 7.5×10^{18}, we observed two

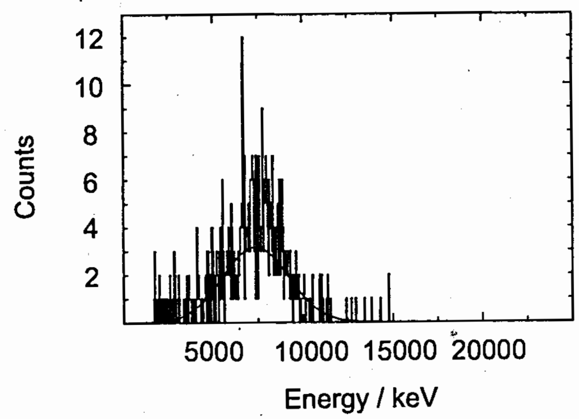

Figure 9: The recorded ER's spectrum from the reaction $^{48}Ca(^{206}Pb,2n)^{252}No$. Only pulses from ER's correlated with the α – decay of ^{252}No were taken into account.

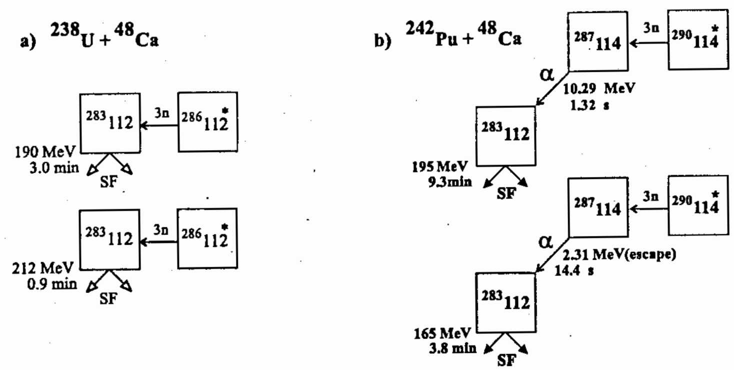

Figure 10: Position-correlated decay chains: a) of $^{283}112$, produced in reaction $^{48}Ca+^{238}U$ [15]; b) of $^{287}114$, produced in reaction $^{48}Ca+^{242}Pu$ [16].

decay chains both consisting of an implanted heavy nucleus, a subsequent α-decay and a spontaneous fission (SF). For the first sequence the measured α particle energy and the corresponding time interval were: E_α=10.29 ±

0.02 MeV and Δt=1.32 s; for the spontaneous fission Δt = 559.6 s. For the second sequence a signal was registered from an α particle, which had escaped the detector, ΔE_α=2.31 MeV, Δt=14.45 s; for the spontaneous fission Δt=228.6 s. The decay chains originated from the α-decay of the new isotope Z=114 with mass number 287 and was terminated by the SF of the previously investigated isotope $^{283}112$. The new nuclide $^{287}114$ was produced in the fusion reaction in the 3n-evaporation channel with a cross section of about 2.5 pb [16].

4 Conclusion

We report a new attempt to synthesize superheavy spherical nuclei in the reactions between ^{48}Ca and ^{238}U, ^{242}Pu targets with the use of the improved detector system of the separator VASSILISSA. We have used an experimental method for the efficient investigation of nuclei near the boundaries of stability. It has been shown that fast and efficient separation in combination with a detector system allowing almost complete registration of α and SF decay channels, high quality electronics and computers for data collection and analysis are adequate tools of investigation of superheavy elements. As a result, it became possible to identify the new isotopes of elements 112 and 114.

As compared with all previous experiments with ^{48}Ca ions [17, 18], the sensitivity of the described experiments is by more than 100 times higher. They are the first step in of our long-term research program with the ^{48}Ca beam, dedicated to the synthesis and study of the properties of superheavy elements. We strongly intend to increase the intensity of the beam, which will allow us to continue these experiments in order to collect more statistics and to make an attempt to synthesize other isotopes with Z = 110 – 116.

Acknowledgments

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