“The SFiNx Detector System”

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The cycle of papers consists of 8 papers.

The phenomenon of spontaneous fission (SF) discovered by G.N. Flerov and K.A. Pietrzak in 1940, turned out to be one of the main decay processes for many heavy nuclei. As further research has shown, this process is very characteristic of superheavy elements and determines the boundary of the existence of atomic nuclei in this region. A significant part of the fission reaction energy goes to the fission fragments excitation and the subsequent evaporation of prompt neutrons. Therefore, the prompt neutron multiplicity carries valuable information about the process dynamics; however, it is one of the least studied characteristics for spontaneously fissile heavy nuclei. Studies of the SF process are of utmost importance for the development of theoretical approaches in fission physics. However, when moving into the region of the heaviest nuclei, significant experimental difficulties arise, which are associated with small cross-sections for production and short lifetimes of synthesized isotopes, what requires researchers to develop the most advanced experimental methods.

A new detector system SFiNx (Spontaneous Fission, Neutrons and X-rays) [1] for on- line investigation of the SF properties of short-lived heavy nuclei synthesized in complete fusion reactions was created in FLNR JINR (Fig. 1).

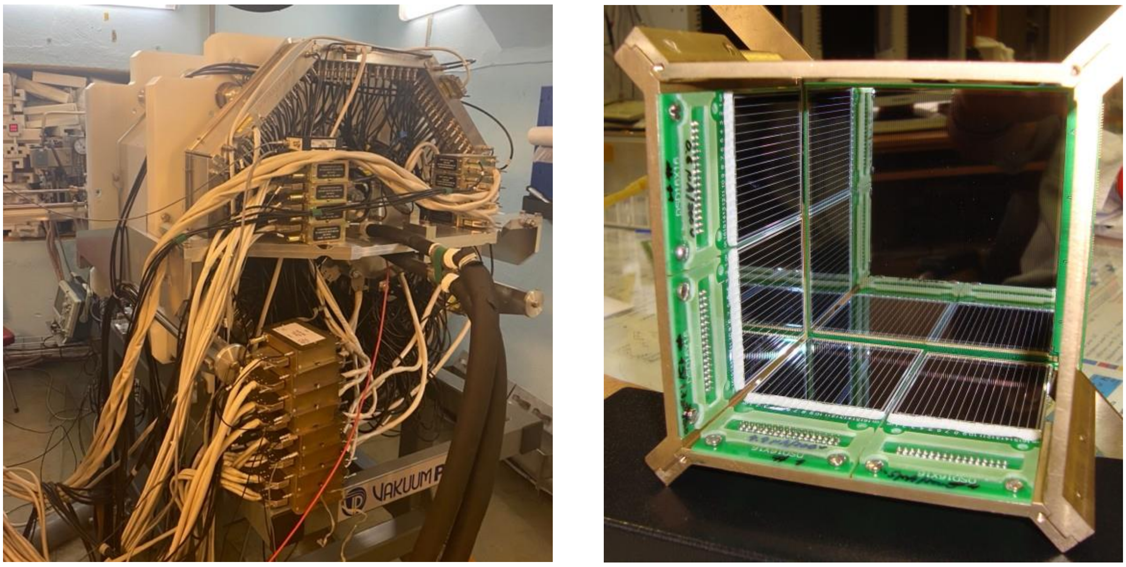

Fig. 1. The SFiNx system (left) and «well» from Si-detectors (right)

The creation of SFiNx is based on the experience of using the neutron detector [A1] and the GABRIELA system for α,β,γ-spectroscopy [A2], which were actively used in experiments on the SHELS separator [A3]. The detector [A1] consisted of 54 ^{3}He-filled neutron counters located around an array of Si semiconductor detectors, in which the focal- plane double-sided strip detector (DSSD) had an area of 60×60 mm. The GABRIELA detection system used a DSSD array with a large focal-plane detector with a size of 100×100 mm. Due to the approximately threefold increase in area, the focal-plane detector of the GABRIELA made it possible to capture a significantly larger number of recoil nuclei (ER). The use of an Si detectors array from the GABRIELA system, inside a neutron detector, would significantly improve the sensitivity of experiments conducted to study of the SF. The increased size of the vacuum chamber for the new DSSD, however, required the substantial modification of the neutron detector configuration.

The selection of the optimal geometry of neutron counters was carried out using Monte Carlo methods for neutron flux simulation in the MCNPX 2.7.0 program. The distance between layers was chosen in such a way that neutrons were thermalized in polyethylene, but the number of used counters was minimal (Table 1). The simulation of a large number of various configurations resulted in the optimal solution with maximum efficiency using 116 counters (Fig. 2).

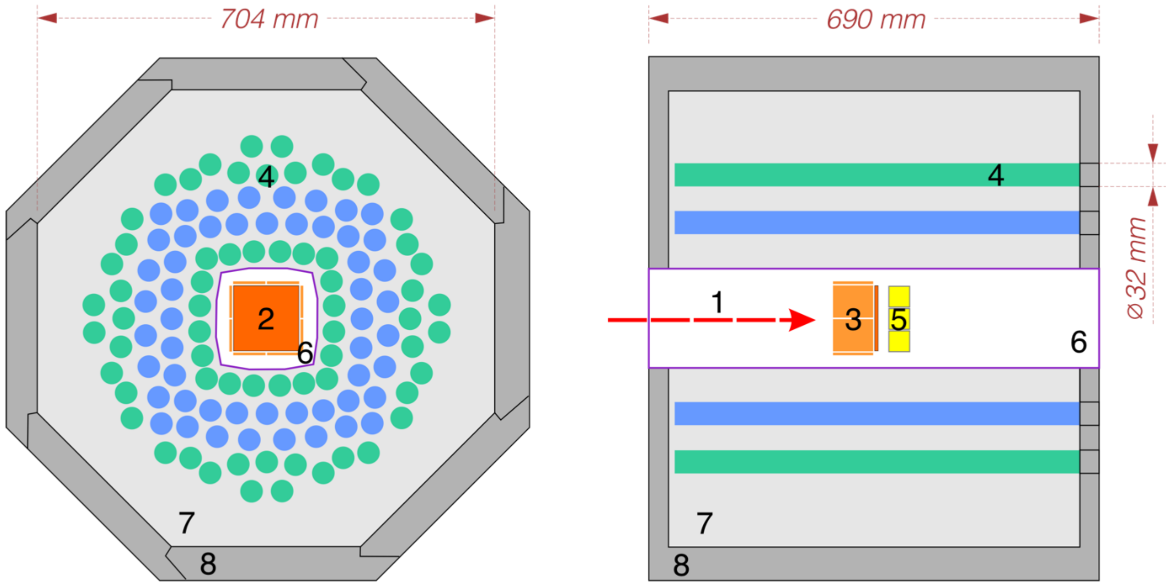

Fig. 2. Scheme of the SFiNx (front view – left; side view – right). The legend: 1 – recoils; 2 – focal-plane Si-detector; 3 – lateral Si-detectors; 4 – ^{3}He-counters; 5 – array of scintillators; 6 – vacuum chamber; 7 – moderator; 8 – shield

Table 1. Characteristics and number of neutron counters in the assembly. Enumeration of counters is given in relation to central axis of the detector

Manufacturer	Diameter, mm	Active length, mm	Working voltage, V	Layer	Number	^{3}He pressure, atm
SPF «Consensus»	32	530	1400	1	20	7
				4	44	
FLNR		460	1775	2	24	
				3	28	

Neutron counters surround a vacuum chamber into which the new DSSD assembly was placed. The focal-plane silicon detector with the 128×128 strips configuration has an active area of 100×100 mm and a thickness of 500 µm. Eight silicon semiconductor detectors are situated perpendicular to the focal-plane detector and form the tunnel assembly (Fig. 1). These lateral 16×16–strip detectors have a size of 50×60 mm, a thickness of 700 μm, and are situated in pairs along each side of the focal-plane detector.

After traversing a time-of-flight detector, the studied ER are implanted inside the focal- plane DSSD, where their subsequent decay takes place. The assembly of Si-semiconductor detectors can be used to register fission fragments and α particles. The detector resolution for α particles with an energy of 8 MeV is 20 and 30 keV for the focal-plane and lateral detectors, respectively. For reducing noise and improving energy resolution, the DSSD assembly is mounted on a cooled holder.

Additional linear amplifiers can be used to adjust the system to the mode of electron registration, which allows one to use the detector for investigating delayed fission and delayed neutrons after β decay.

Prompt neutrons produced in the SF are slowed down in polyethylene to thermal energy and, hitting neutron counters, are captured by ^{3}He nuclei. The external part of the detector is covered by plates from borated (5%) polyethylene with a thickness of 50 mm along the moderator prism height and 30 mm at the bases for protection from background neutrons.

Since the process of the SF is accompanied by the emission of a large number of γ quanta, gamma coincidences can be an additional factor for cleaning away background pulses with large amplitudes in the DSSD. An array of 9 CLLBC scintillator detectors was installed directly after the focal-plane DSSD for registration of γ quanta.

Measurements of prompt neutrons from the SF of ^{248}Cm were performed to verify the detector operation and a more specific determination of its characteristics. The source was placed on a thin foil, which was then installed at the center of the DSSD array, 5 mm from the focal-plane detector. When a fission fragment was detected in the data, neutron events in an interval of 0 – 128 μs were sought. The energy window for the search of fragments was chosen in such a way that false correlations with α particles from the source were completely eliminated. To determine the exact value 55±1 % [2] of the single neutron registration efficiency, the nonlinear least-squares method was used. The distribution of times between fission fragments and neutrons was used for determining the average neutron lifetime in the assembly, this value was determined as 18±1 μs.

An experimental series was carried out on the modernized kinematic separator of recoil nuclei SHELS [A1] at FLNR JINR to study the SF properties of short-lived isotopes of transfermium elements [2–4]. The nuclei under study synthesized in complete fusion reactions of ^{40}Ar, ^{48}Ca and ^{54}Cr ions accelerated on the U-400 cyclotron with targets from enriched isotopes ^{204,206,207,208}Pb. The SHELS carried out the separation of the desired recoil nuclei from the products of side reactions and scattered ions of the beam. After the separation step, recoil nuclei flew through the time-of-flight detector and implanted into the focal-plane double sided Si-strip detector of the SFiNx system, where their further decay occurred.

Since the efficiency of neutron detection by counters is far from 100%, the multiplicity distribution observed in the experiment is highly distorted compared to the original one and requires a restoration procedure. High statistical efforts associated with small formation cross-sections of recoil nuclei and the error in determining the efficiency of the detector transfer the problem to the category of mathematically incorrect ones, which requires the use of special mathematical methods to reconstruct the true neutron multiplicity distributions from the measured ones (Fig. 3). To solve this problem, the Tikhonov method of statistical regularization used. It was successfully adapted for the SFiNx detection system experimental data analysis [5].

It is worth mentioning that the detection setup at the focal plane of the separator is situated behind a 2 m-thick concrete wall, which substantially reduced the background from neutrons and γ quanta produced on the Faraday cup and the target. The influence of the background was insignificant in comparison with the level of statistical efforts obtained in experiments [3].

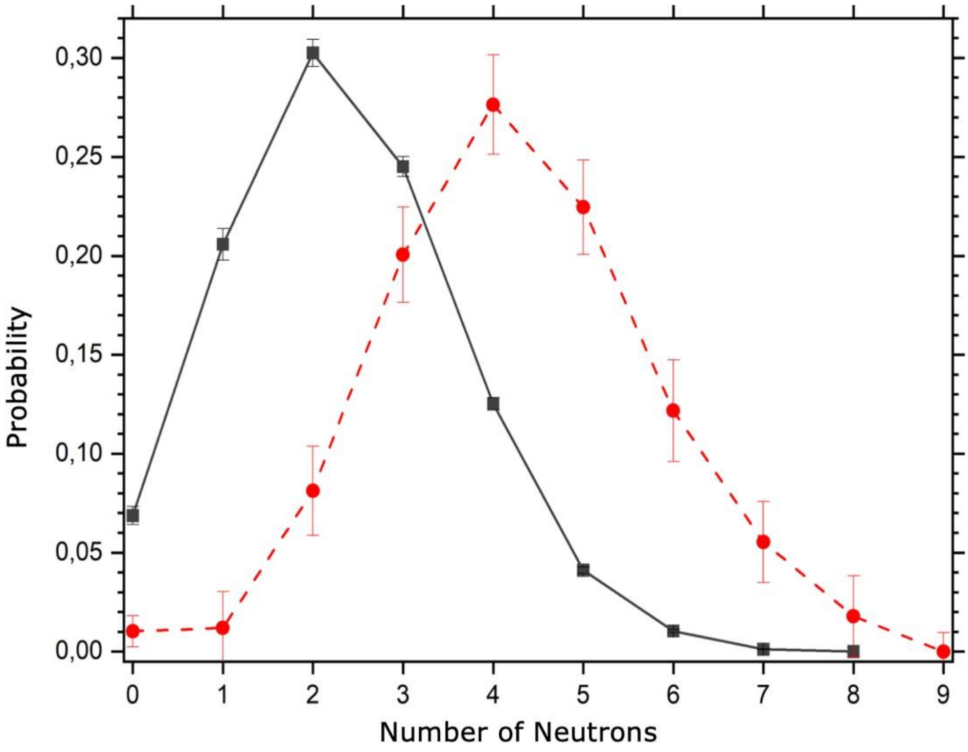

Fig. 3. Measured (squares) and restored (circles) prompt neutron multiplicity distributions from ^{252}No spontaneous fission

As a result of an experimental series, the prompt neutrons yield data from spontaneous fission obtained for the first time for the isotopes ^{250}No and ^{260}Sg, and significantly refined for the isotopes ^{244,246}Fm and ^{252}No (see Table 2). The updated systematics of the average number of neutrons per the SF act (Fig. 4) shows a continuing general trend towards an increase in the values of this characteristic when moving towards heavier nuclei.

Table 2. Characteristics of the prompt neutron emission from the SF of heavy nuclei

Isotope	**Average number of neutrons per SF act**	**Dispersion of distribution**	**Emission probabilities**
^{244}Fm	3,5±0,2	1,4	substantially refined
^{246}Fm	3,8±0,3	2,1	substantially refined
^{250}No	4,1±0,1	1,8	received for the first time
^{252}No	4,25±0,09	2,1	substantially refined
^{260}Sg	4,9±0,4	3,0	received for the first time

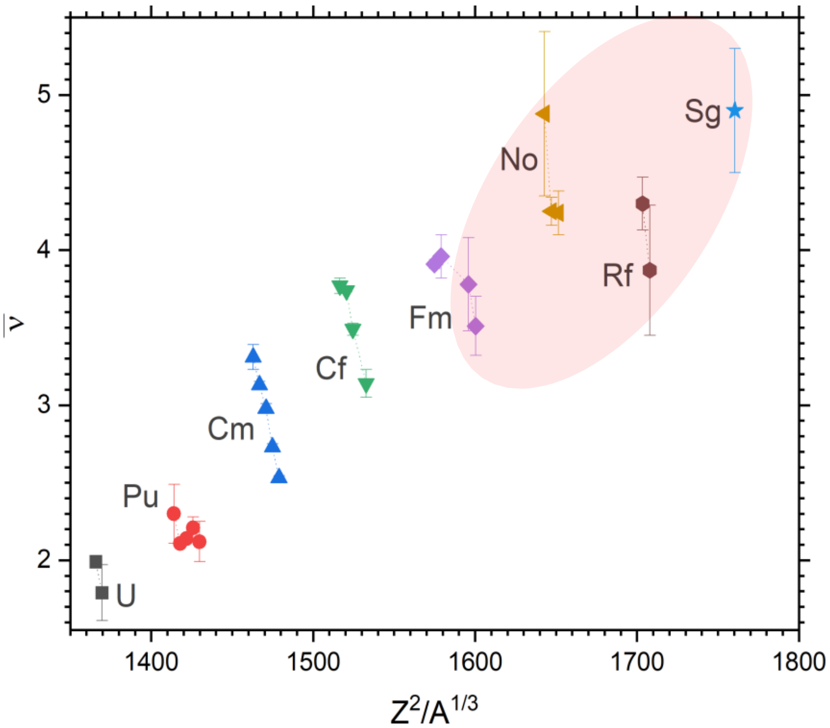

Fig. 4. Systematics of the average number of neutrons per the SF act. The oval marks the data obtained with the SHELS separator

The most important feature of our experimental series was the ability to obtain data not only for the first two moments of prompt neutron distributions (average number and dispersion) but also for the shapes of neutron multiplicity distributions, which contain information about the dynamics of the SF process [A4, 8]. As seen from the systematic on Fig. 5, the distribution shapes are unique for each isotope and could be separated into symmetric and asymmetric ones. The latter may be especially valuable for searching for fission modes of heavy nuclei [A4].

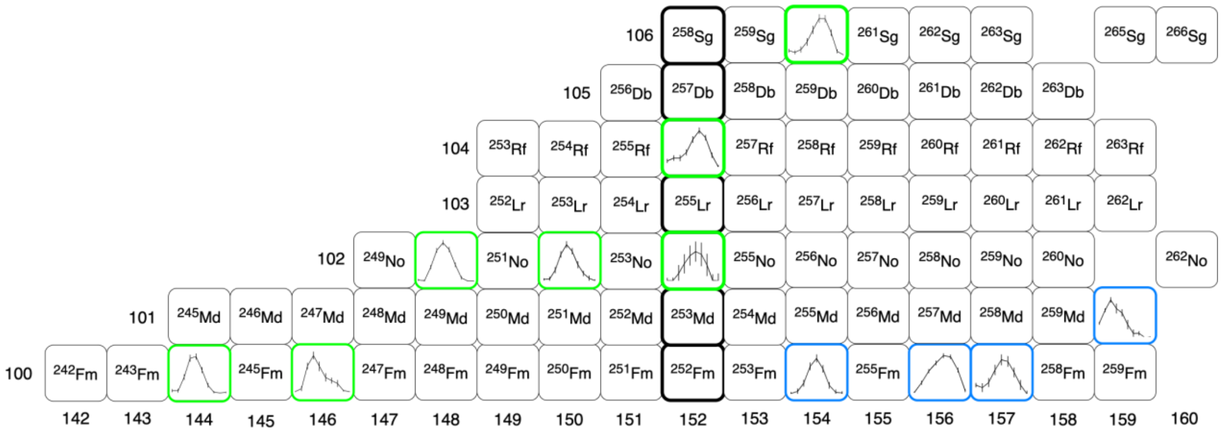

Fig. 5. The prompt neutron multiplicity systematics for isotopes of transfermium nuclei. The data obtained using the SHELS separator highlighted in green.

The SFiNx detection system also combined with digital electronics (National Instruments) for collecting and processing waveforms, what is useful for finely tune neutron counter thresholds, and allows us to analyze time correlations at the level of tens nanoseconds [6–7]. The capabilities of SFiNx digital electronics were tested during an experiment on the SHELS separator to study the decay properties of the neutron-deficient ^{250}No isotope [4].

Thus, a highly efficient detection system created for studying the spontaneous fission of short-lived heavy nuclei. The use of SFiNx will make it possible to advance research into the field of superheavy elements, where there is currently no data on the yield of prompt neutrons and the total kinetic energies of fission fragments. The system can be used on the GRAND gas-filled separator, recently launched at the Superheavy Elements Factory of FLNR JINR.

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1. A.V. Isaev, A.V. Yeremin, N.I. Zamyatin, I.N. Izosimov, A.A. Kuznetsova, O.N. Malyshev, R.S. Mukhin, A.G. Popeko, Yu.A. Popov, B. Sailaubekov, A.I. Svirikhin, E.A. Sokol, M.S. Tezekbayeva, D.A. Testov, M.L. Chelnokov, V.I. Chepigin, S. Antalic, P. Mosat, P. Brionnet, B. Gall, O. Dorvaux, K. Kessaci, A. Sellam, A. Lopez-Martens, K. Hauschild, "Study of spontaneous fission using the SFiNx system", Acta Physica Polonica B Proceedings Supplement, No 4, Vol. 14 (2021).
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