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# Investigation of the spontaneous fission properties of neutron-deficient nobelium isotopes

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In the last years we carried out several experiments aimed to investigate properties of short-lived SF isotopes. The neutron-deficient isotopes of nobelium were produced in fusion-evaporation reactions using $^{206,208}$Pb targets and an intense $^{48}$Ca-beam. Fusion-evaporation residues were separated by the SHELS separator and implanted into a large-area double-sided (48 × 48) strip silicon detector surrounded by $^{3}$He-based neutron counters. Half-lives and decay branching ratios for $^{252,254}$No isotopes were measured. The average number of neutrons per spontaneous fission of $^{254}$No determined for the first time.

**Keywords:** neutron multiplicity, spontaneous fission, fission fragment.

## Separator and Detectors

Main purpose of our experiments is collection of data about characteristics of spontaneous fission of short-lived nuclei from transfermium region. Separator for Heavy ELement Spectroscopy (SHELS) was used, see Figure 1. SHELS consists of two triplets of magnetic quadrupole lenses and velocity filter that are formed by two dipole magnets and two electrostatic deflectors [1].

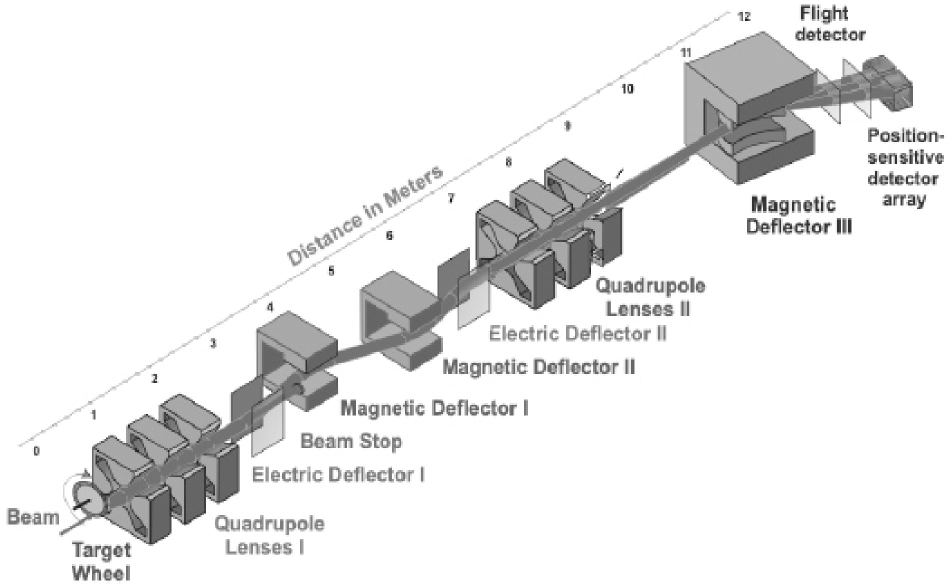


Figure 1. SHELS separator.

At the focal plane of separator, the combined detection system placed. After MCP-based time of flight detectors, reaction products from separator implanting to $48 \times 48$ strip silicon detector [2], see Figure 2.

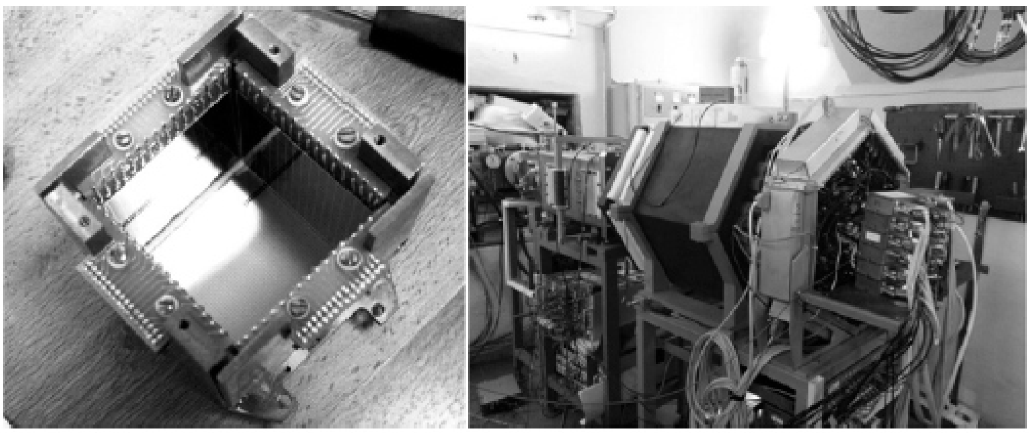

Figure 2. Array of silicon strip detectors (left) and neutron detector (right).

The detector has ($58 \times 58$ mm$^2$) active area and 300 μm thickness. Energy resolution is 20 keV for $\alpha$-particles with 6-8 MeV. Detection efficiencies of focal detector are 50% for $\alpha$-particles and 100% for at least one fission fragment. For the total fission fragment energy calculation, we using symmetrization of focal plane and side detectors signals, detection efficiency in this case is about 70%.

Neutron detector, surrounding silicon detectors array, consist of 54 $^{3}$He neutron counters, see Figure 2. Pressure in counter is 7 atm. Each counter has length 500 mm and diameter 32 mm. Neutron detector allows us to detect multiple prompt neutrons from the spontaneous fission of registering nuclei [3]. Counters were placed in polyethylene moderator. Neutrons registration triggered by DSSSD detector. Neutrons waiting gate is 128 μs and it opens immediately after detection of fission fragment. The average lifetime of a single neutron before it's captures by the He-3 counter or before it's departure beyond bound of the detector is about 25 μs. The neutron detection efficiency measured with the $^{248}$Cm source is 45 ±1 % for a single neutron.

## Experiments and Data Analysis

The experiments were carried out in January 2015 at the U-400 cyclotron of Flerov Laboratory. Cross-section of 2n-channel of ($^{208}$Pb+$^{48}$Ca) reaction is about 1800 nanobarns. The cross-section for the same evaporation channel of ($^{206}$Pb+$^{48}$Ca) reaction is about 800 nanobarns. Beam intensity was 0.5 pμA and beam energy was (215 ± 2) MeV.

The main interest for us was related to the first reaction. The second reaction was used for calibration purpose mostly.

A highly enriched $^{208}$PbS target (370 μg/cm$^{2}$) was used for $^{254}$No synthesis. Enrichment by $^{208}$Pb was about 99.6%. But despite such enrichment the target still contained admixtures: $^{206}$Pb ≈ 0.14% and $^{207}$Pb ≈ 0.29%, this leads to some difficulties in the data analysis. For $^{252}$No synthesis $^{206}$PbS target (350 μg/cm$^{2}$) was used.

The reaction cross-section for $^{254}$No synthesis is huge, but the spontaneous fission branching ratio for this isotope is very small, it's only about 0.17% [4]. The calculated value of the number of spontaneous fissions of $^{254}$No should have been about 175 events. We calculate this value based on the number of registered $\alpha$-particles with detection efficiency about 50% and we took into account that detection efficiency for two fission fragments is about 70%.

With correlation analysis, we got 115 fission events of $^{254}$No. In order to get rid of the high-energy background we did a search only of fission fragments –recoil correlations in the time interval from 15 to 200 seconds. For reliability, we filter out events with only one fission fragment detected (both signals from side and focal detectors must be found).

A fission fragments spectra was obtained using summarization of energy from focal and side detectors, see Figure 3. TKE data for $^{254}$No was approximated based on the known value of TKE for $^{252}$No. Received value of TKE for $^{254}$No is about 184 MeV. Measured multiplicity of neutrons (these values do not include detector efficiency) was 2.2 neutrons per act for $^{254}$No and 1.89 neutrons per act for $^{252}$No. Thus, we see that the total kinetic energy decreases in inverse proportion to the average number of neutrons per SF.

Half-lives received in discussed experiments were (2.76 ±0.18) s for $^{252}$No and (55 ± 5) s for $^{254}$No. Average number of neutrons per spontaneous fission act

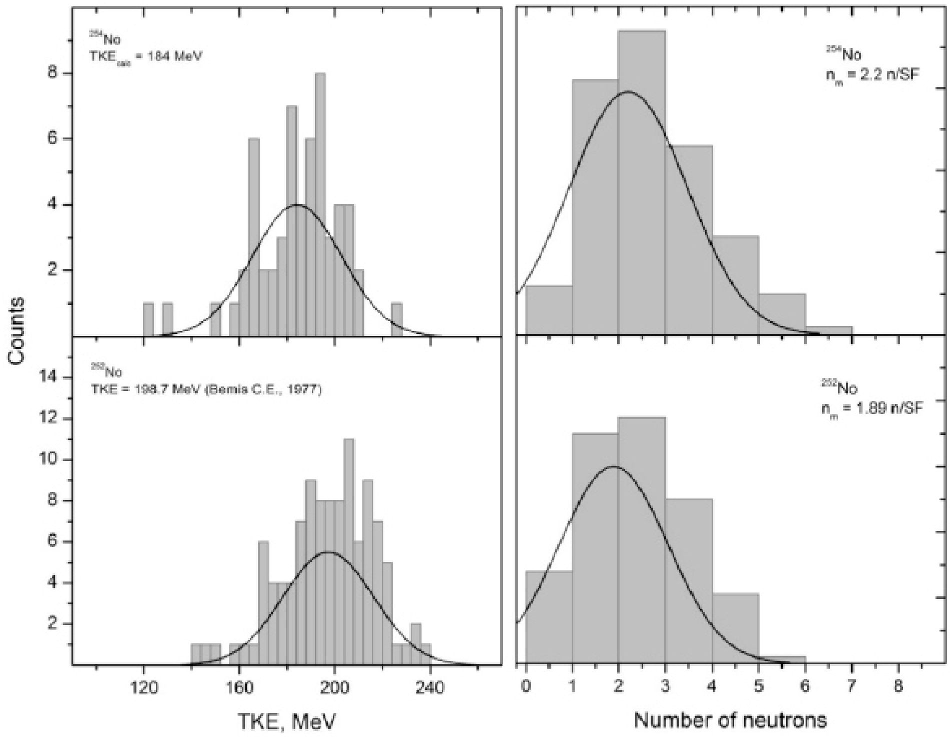


Figure 3. Measured SF-properties of $^{252,254}$No isotopes.

were determined (the efficiency of neutron detector taking in to the account) as $(4.33 \pm 0.17)$ for $^{252}$No and $(5.07 \pm 0.27)$ for $^{254}$No, see Figure 4.

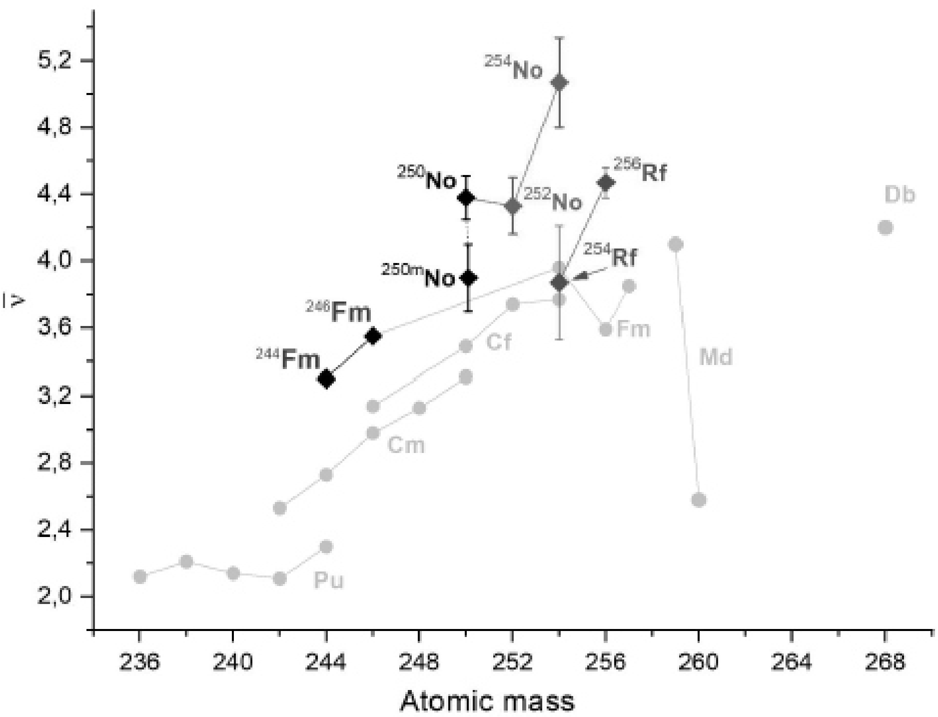


Figure 4. Average number of neutrons per fission as a function of the atomic mass.

## Detectors Upgrade

We are planning to upgrade our detectors. The size of focal plane DSSSD will increase from $(60 \pm 60)$ mm$^2$ to $(100 \times 100)$ mm$^2$. This will allow us to improve transmission efficiency about 2-3 times. Another goal will be unification of silicon detectors array and electronics with GABRIELA setup [1]. Current vacuum chamber with DSSSD is cylinder with diameter 130 mm. It will be replaced by rectangular cuboid with focal size $(155 \times 155)$ mm$^2$. The Neutron-geometry application was created to automate the process of new geometry definition [5]. When the new geometry constructed user will be able toexport it to MCNPX input file format [6]. The best result we found was for geometry with square layers, see Figure 5. We got neutrons registration efficiency about 57% using 116 counters.

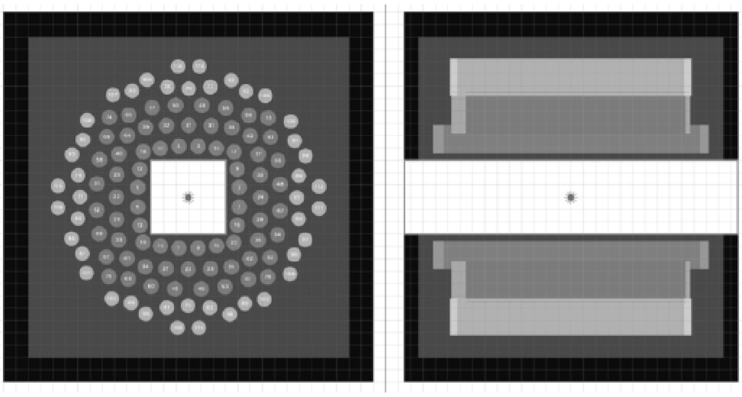

Figure 5. The optimal geometry. A grid step is 25 mm.

## Conclusion

Various characteristics of spontaneous fission of $^{252,254}$No isotopes were measured. The average number of neutrons per spontaneous fission of $^{254}$No is $5.07 \pm 0.27$. This value determined for the first time.

The new neutron detector configuration found. Our efforts to reach the maximum efficiency to be continue. The Neutron-geometry application solution can be reused for similar tasks.

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