

On the role of initial conditions in background suppression for fusion-evaporation reactions

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Abstract

A new approach is presented for optimizing the application of the active correlations method for substantial background suppression in experiments aimed at detecting rare alpha-decay and spontaneous-fission events in complete-fusion nuclear reactions. The proposed optimization steps concern parameters such as the minimum energy of signals attributed to nuclei implanted into a silicon DSSD detector, the time-correlation interval, and the relative loss of target irradiation time. A test using a silicon n-Si(Au) detector and a special ICS-119 unit is described. The amplitude spectrum of registered signals for a nucleus with $Z = 119$ is calculated for the DGFRS-2 setup at FLNR JINR using an additional thin aluminum absorber to reduce the background from short-range heavy particles. It is assumed that these parameters will be used in the upcoming experiment $^{249}\text{Bk} + ^{50}\text{Ti} \rightarrow 119^*$ in the near future. The background load is estimated on the basis of the experiment $^{242}\text{Pu} + ^{50}\text{Ti} \rightarrow \text{Lv}^*$. In this context, the present work can be considered a continuation of several previous studies devoted to the detection system and to the improvement of the "active" correlations method in complete-fusion reactions with heavy ions.

1 Introduction

The achievements of nuclear physics in the 21st century are primarily associated with a series of successful experiments on the synthesis of new chemical elements and the study of the properties of superheavy nuclei [1–6]. These results became possible not only due to the use of intense heavy-ion beams and exotic actinide targets, but also due to the development of highly sensitive detection systems that make it possible to reliably extract rare α -decay events from the overall data flow [7–10].

One of the specific features of experiments performed at FLNR JINR is the application of the active correlations method, which provides radical suppression of background signals associated with accelerator operation. In the present work, further improvement of this method is considered using a flexible algorithm for searching for rare correlated decay events. Particular attention is paid to the upcoming experiment on the synthesis of element $Z = 119$, planned for 2026. Based on available literature data, optimal input parameters for applying the method are proposed, including the correlation time interval and the minimum registered energy of the recoil nucleus. In addition, possible reasons for the small discrepancy, at the level of a few percent, between the registered amplitudes of implanted heavy recoil nuclei and the calculated values are discussed.

2 Method of active correlations

A key point of any nuclear physics experiment aimed at searching for rare decay events is the use of a detection system that makes it possible to separate the desired decay events of the nuclide of interest from background events that may imitate them. Since intense heavy-ion beams with intensities up to several $\text{p}\mu\text{A}$ are used to increase the overall sensitivity of such experiments [11], the importance of efficient background suppression becomes especially high. The detection system of the DGFRS-2 setup at FLNR JINR is described in detail in Refs. [7–9, 12–15].

The active correlations method [8, 14] is used for strong background suppression. Briefly, the idea of the method is as follows: after registration of a correlated ER– α energy–time–position sequence, the cyclotron beam is switched off, and subsequent α decays and/or spontaneous fission events of daughter products are registered under nearly background-free conditions. This method is effective when the initial correlation conditions are properly chosen, namely the recoil and α -decay energies and the expected lifetime of the studied nuclide. Since these properties are not known a priori, they are usually estimated on the basis of theoretical models and systematics.

In Ref. [8], lifetime estimates were obtained using Eq. (1) of that work and compared with experimental data for nuclei with $Z > 100$ [1, 2]. Figure 1 shows the comparison between calculated and experimental values using the parameter $\lg K = \lg(T_{\text{calc}}/T_{\text{exp}})$.

For the recoil energy, calculations for the reaction $^{249}\text{Bk} + ^{50}\text{Ti} \rightarrow 119^*$ were reported in Ref. [16]. Figure 2 shows a similar calculated spectrum of the implanted $Z = 119$ nucleus, but with an additional $0.8 \mu\text{m}$ Al absorber placed in front of the detection module. This absorber is used to reduce the radiation load on the focal-plane DSSD detector of the DGFRS-2 separator.

According to the adopted formula, the calculated half-life of the $Z = 119$,

$A = 296$ nucleus is about $156 \mu\text{s}$. The corresponding results for nuclei with $Z = 119$ and $Z = 120$ are presented in Table 1. The parameters for the daughter nucleus ^{292}Ts are given after the slash.

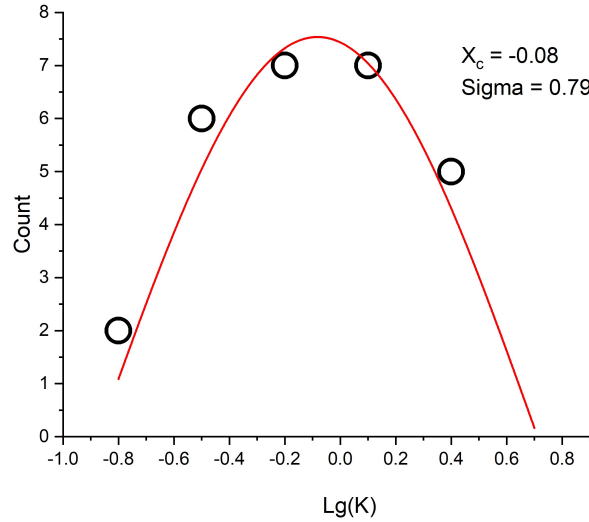


Figure 1: Dependence of the parameter $\lg K = \lg(T_{\text{calc}}/T_{\text{exp}})$ from Ref. [8].

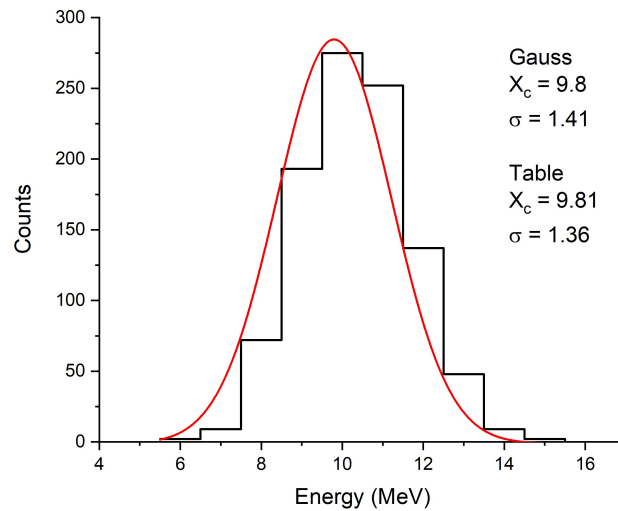


Figure 2: Spectrum of the registered energy of the $Z = 119$ nucleus based on calculations from Ref. [16].

Thus, as a reasonable scenario, the correlation time interval can be estimated as

$$t_{\text{EVR}-\alpha} = 10 \cdot T_{1/2} \cdot 10^{2\sigma_{\log K}}, \quad (1)$$

where $\sigma_{\log K}$ is the standard deviation of $\log K$. According to Figure 1, $\sigma_{\log K} = 0.79$, while for $^{296}119$ the half-life is $T_{1/2} = 156 \mu\text{s}$, as given in Table 1. Substitution of these values gives

$$t_{\text{EVR}-\alpha} = 10 \cdot 156 \mu\text{s} \cdot 10^{2 \cdot 0.79} \approx 60 \text{ ms}. \quad (2)$$

The factor of 10 is introduced to provide statistical reliability of the decay-event registration, corresponding to a confidence level of approximately 0.999.

Table 1: Half-lives of nuclei with $Z = 119$ and $Z = 120$. The symbol * indicates the calculated value reported in Ref. [17].

Isotope, reaction channel	Q_α (MeV)	$T_{1/2}$
$^{296}_{119}\text{Ts}$ (3n) / $^{292}_{119}\text{Ts}$ / $^{288}_{119}\text{Mc}$	12.265 / 11.3 / 10.4	156 μs / 8 ms / 164 ms
$^{295}_{119}\text{Ts}$ (4n)	12.367	93 μs
$^{297}_{120}\text{Uuq}$ (3n)	12.772 (13.14*)	22 μs (12 μs^*)
$^{296}_{120}\text{Uuq}$ (4n)	12.874	13.5 μs

Accordingly, for the isotope $^{297}_{120}\text{Uuq}$, using $T_{1/2} = 22 \mu\text{s}$, the estimated correlation time interval is

$$t_{\text{EVR}-\alpha} = 10 \cdot 22 \mu\text{s} \cdot 10^{2 \cdot 0.79} \approx 8.4 \text{ ms.} \quad (3)$$

If the decay characteristics of daughter products are taken into account, the indicated time intervals may be increased.

3 On the lower limit for the registered EVR energy

Although the calculated amplitude spectrum of heavy nuclei implanted into a silicon detector is generally in good agreement with the measured spectrum, about 2–3% of events lie outside the $\pm 3\sigma$ range [7, 16]. Therefore, an approach in which the lower energy threshold for evaporation residues (EVRs) is set as low as possible is preferable. The limiting factor in this case is the increase in the frequency of cyclotron beam stops, which leads to a reduction in the target irradiation time and, consequently, to a decrease in the overall efficiency of the experiment.

In this situation, it seems reasonable to use the relative loss of irradiation time as an optimization parameter for the data acquisition program and for setting the minimum recoil energy threshold. The choice of such a parameter is facilitated by the fact that, in the irradiation-dose accumulation mode, the heavy-ion beam intensity of the DC-280 cyclotron at FLNR JINR is rather stable. Therefore, the new version of the C++ data acquisition program YDA-2026, see also Ref. [14], includes functions that make it possible to estimate irradiation time losses online for preset beam-stop parameters. These parameters are read from a text file when the program is loaded and a new acquisition file is opened.

Figure 3 shows a block diagram of the data acquisition process. The selection of the optimal value of the minimum registered energy of the implanted nucleus is possible both in interactive and automatic modes. In the automatic mode, an additional timer is started. In this case, the experimenter must be confident that sufficient statistics have been accumulated and should start the timer using the corresponding item in the main program menu. The input parameter for such optimization is the allowable irradiation-time loss specified by the experimenter in interactive mode. The output parameter, namely the recoil energy threshold, is written to a preliminary parameter file, after which the data acquisition program is restarted with the new recoil-energy threshold.

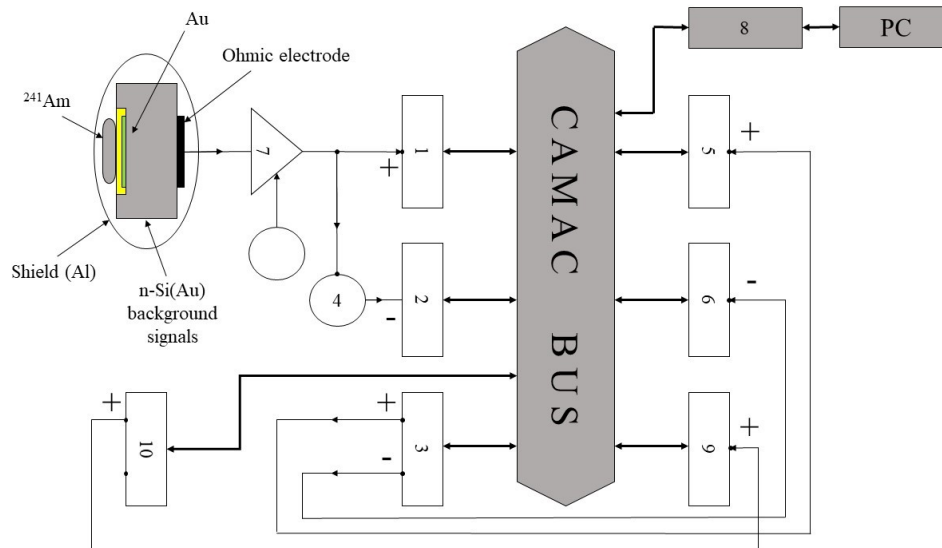


Figure 3: Block diagram of the test setup used for searching for generated correlation sequences. The detector is shown schematically and is located inside an aluminum housing.

As for the physical reasons for the appearance of amplitudes outside the $\pm 3\sigma$ interval at the level of a few percent, see Figs. 4 and 5 in Ref. [16], possible contributions may be associated with such effects as channeling of heavy ions in the silicon lattice and recombination in a system of non-stationary defects [18]. At the level of an empirical correction, the following modifications can be introduced into the computer simulation program for the spectrum of implanted heavy nuclei:

- in approximately 1.5% of cases, the amplitude defect calculated using the Wilkins formula [19] can be neglected. This correction mainly affects the right-hand side of the distribution;
- in another 1.5% of cases, it can be assumed that the registered energy may be significantly lower than the generated amplitude. Thus, if the generated value is E_i , then with probability $p_i = 0.015$ the final value is taken as a random variable uniformly distributed in the interval $(0, E_i)$ before being written to the final event list.

4 Test with an external alpha-particle source

Before operation with the DC-280 cyclotron beam, the electronic modules are usually tested on a laboratory bench using the α activity of a ^{241}Am source deposited directly onto the surface of a surface-barrier $n\text{-Si(Au)}$ detector. Signals from this detector are used as background signals with a count rate of about 50 Hz. In some tests, these signals play the role of implanted recoil signals. The signals simulating EVR- α and/or α - α correlations are generated through the CAMAC bus by a special 1M ICS-119 module (“ExTech”, Dubna; see Refs. [17, 20]).

The generation of correlated events is initiated either by pressing a button on the front panel of the ICS-119 module or by a software command. The block diagram

of the test setup is shown in Figure 3. The numbered components are as follows: 1, 2, 5, and 6 are ADP-16 analog 16-input processors; 7 is an SP-281 charge-sensitive preamplifier of custom design; 3 is the ICS-119 module used for generating correlated links; 4 is an inverting amplifier of custom design with a gain of approximately unity; 8 is the crate controller; and 9 and 10 are the ADP and ICS-119 modules used for testing the side detectors, respectively. The signals corresponding to the horizontal and vertical strips have opposite polarities, as indicated in the block diagram by the “+” and “-” signs. The bias-voltage circuit is located inside the charge-sensitive preamplifier and supplies +18 V to the ohmic contact of the detector. A typical spectrum of signals attributed to background events is shown in Figure 4.

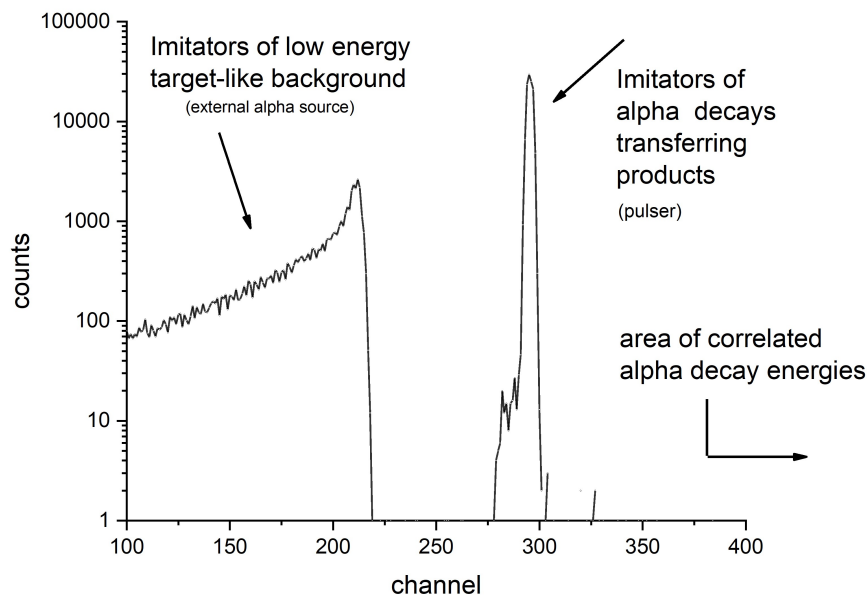


Figure 4: Spectrum of signals attributed to background events.

The total count rate of the signals shown in Figure 4 is approximately 150 Hz, which roughly corresponds to the count rates observed with a heavy-ion beam at an intensity of about 1–1.5 pμA. The results of the correlation search are presented in Table 2. The following input parameters were used: recoil energy interval of 4000–19500 keV, α-particle energy interval of 9200–13800 keV, correlation time of 340 μs, and beam-off pause of 60 s.

Events that cause interruption of target irradiation are recorded in a text file, which becomes available to the experimenter after closing the data file.

It should also be noted that immediately before irradiation, the detection system is tested on the DGFERS-2 separator using a ^{238}Pu α-particle source. In this test, a significant fraction of the signals, more than 95%, is treated as recoil-nucleus imitators, while the remaining part is treated as α particles. As a result, correlated energy–time–position (X, Y) “EVR”–α links are recorded and written to the output file `STOP.txt`.

Table 2: Examples of correlation-search results. Correlation signals were generated by the ICS-119 pulse module [20].

α -particle energy, keV	Time since file opening, $10 \mu\text{s}$	Time between EVR and α particle, $10 \mu\text{s}$	Horizontal strip number	Vertical strip number
9731.7	1239231	31	14	72
10624.6	27292536	31	14	72
10521.4	35416631	31	14	72
10037.6	45422748	30	14	72
10393.4	53392842	31	14	72
10458.4	33654714	30	41	66
10260.9	68233229	30	41	66

5 The $^{242}\text{Pu} + ^{50}\text{Ti}$ reaction for determining background-load parameters at an intensity of $1.5 \text{ p}\mu\text{A}$

A rotating ^{242}Pu target was irradiated with ^{50}Ti ions at the DC-280 cyclotron of FLNR JINR. The beam intensity was about $1.5 \text{ p}\mu\text{A}$. A typical dependence of the recoil-nucleus imitator count rate on the minimum registered energy threshold is shown in Figure 5. At the same time, the average count rate in the energy range of 9000–12500 keV, corresponding to α -particle energies, was about 0.611 s^{-1} .

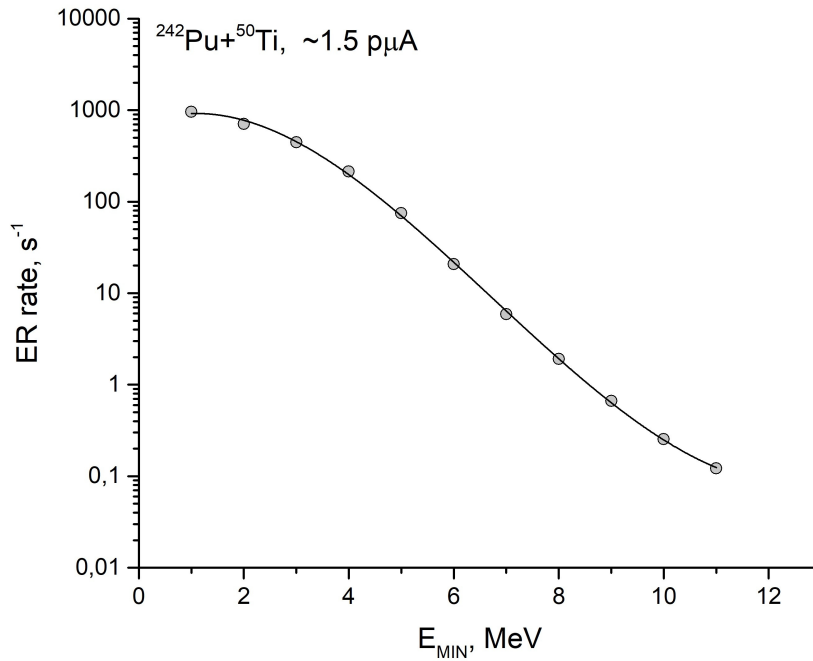


Figure 5: Dependence of the recoil-nucleus imitator count rate on the minimum registered energy threshold. The solid line shows a third-degree polynomial approximation.

Thus, for example, if the minimum recoil-nucleus energy is set to about 5 MeV,

then for a correlation time interval of 60 ms and for the effective detector area, the corresponding irradiation-time losses can be estimated. These estimates are relevant for applying the active correlations method for radical background suppression under the given background-load conditions and for the input parameters listed in Table 2.

6 Alpha-Particle Signals Recorded by the Side Detectors

Since the count rates of the side detectors during the experiment are much lower than those of the focal-plane detector, it becomes possible to use, as a trigger for beam interruption, a correlation between an implanted recoil signal in the focal DSSD detector and an α -decay signal in a side detector, regardless of the recoil-nucleus coordinate. It should be taken into account that the energy recorded by a side detector is lower than the nominal α -particle energy, since part of the energy is deposited in the DSSD detector. It should also be noted that, in the test mode shown in Figure 3, the side detectors have only one-sided strips; therefore, the corresponding ICS-119 module generates signals of only positive polarity.

Table 3 presents characteristic values of the average time between recoil signals and α -particle signals registered by the side detectors. Based on these data, one can estimate the number of random correlations of this type, taking into account that the registered energy differs from the nominal value by approximately a factor of 0.92 for a nominal α -particle energy of 9.26 MeV. The data in the table correspond to the $^{242}\text{Pu} + ^{50}\text{Ti}$ reaction at a beam intensity of about $2 \mu\text{A}$.

This capability is implemented in the current version of the YDA-2026 program. The correlation time for this beam-stop procedure is set separately from the correlation time used for the focal DSSD detector, as discussed in the previous sections. Typically, this parameter is shorter than that used for the DSSD EVR- α correlation. This approach is expected to be especially useful for nuclides with very short decay times, where fast and simple triggering conditions are required.

Table 3: Characteristic average times between recoil signals and α -particle signals registered by the side detectors.

Registration threshold, MeV	7	8	9	10	11
Average time, s	0.14	0.42	1.15	2.7	4.7

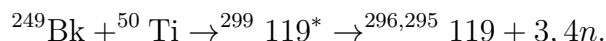
7 Conclusion

With the development of digital technologies, the active correlations method is expected to be applied in increasingly diverse forms [13]. At the same time, the further improvement of high-intensity heavy-ion accelerators and recoil separators requires a more rigorous and flexible choice of the initial parameters used in this method. The higher the heavy-ion beam intensity, the more important it becomes to optimize the conditions for background suppression while minimizing losses of target irradiation time.

In this work, a new algorithm was proposed and tested for optimizing such input parameters as the EVR- α correlation time and the lower threshold of the registered

energy of implanted recoil nuclei. The algorithm can operate both in interactive and fully automatic modes, thereby expanding the capabilities of the YDA-2026 data acquisition program [14]. In addition, the proposed procedure for registering EVR- α correlations involving side detectors extends the applicability of the active correlations method, especially for nuclei with short decay times.

The obtained parameters make it possible to apply the developed approach in the upcoming experiment on the synthesis of element $Z = 119$ in the reaction



According to the estimates presented in Table 1, the calculated half-life of the daughter product ^{292}Ts is about 8 ms. Therefore, the proposed correlation interval of 60 ms corresponds to approximately eight half-lives of this daughter nucleus. This interval provides a reasonable compromise between reliable registration of correlated decay chains and acceptable losses of target irradiation time.

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