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Study of Solar Activity Correlations with ^{55}Fe, ^{60}Co Nuclear Decay Parameters

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Abstract—Temporal variations of nuclear decay parameters actively studied now; their detection may be a signal of new physical effects of cosmic origin, in particular, due to influence of solar processes. In some recent experiments annual and daily oscillations of unstable nuclei α- and β-decay parameters were observed at a level about 0.05%. Correlations of intensity of ^{60}Co, ^{54}Mn and ^{55}Fe weak decays with solar activity, in particular with solar flares, were observed. In our work, correlations of X-class solar flares with ^{60}Co and ^{55}Fe decay rate parameters were studied, their measurement were performed by means of decay γ-ray detection by semiconductor detectors. For ^{55}Fe decay eight significant deviations of decay counting rate in form of reduction from the expected rate were observed at the level ~0.2% correlated with solar flares. For ^{60}Co decay four similar events were detected with deviations at a level of ~0.4%. All decay rate deviations have advanced character and begin from 30 to 155 h before solar flare moments with a confidence level of 90%.

Keywords: nuclear decay, solar activity, solar flare

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INTRODUCTION

It is acknowledged currently that the decay parameters of radioactive nuclei are time invariant and practically unaffected by their environment [1]. However, in some experiments time modulations of nuclei α- and β-decay radioactive isotope constants were observed at a level of about 10^{-3} and with periods of one year, one day or several months [2–7]. In the main bulk of publications, the annual sinusoidal oscillations of β-decay rate of different heavy nuclei from Si to Ra; for most of them the oscillation amplitude was approximately 0.05% with its maximum at about mid-February [2, 3]. Oscillations of decay electron energy spectra with 6 months period were found also in tritium β decay [5]. Experiment Tau-2 measured α-decay life-time for short-living isotopes ^{214}Po, ^{213}Po [6]. The annual and daily oscillations with amplitude of the order 6×10^{-4}, with annual maxima at mid-March and daily maxima around 6 a.m. were found for both isotopes. Analogous annual oscillations were obtained for ^{212}Po [7]. Such types of periodicity allow to assume that such variations may have a cosmophysical origin. Theoretical models describing such effects considered in [3, 8]. Note that some other experiments exclude for β decay and inverse β decay of heavy nuclei the annual constant modulations as large as reported ones [9, 10].

Other studies in this area concern with the possible influence of solar activity, in particular, the correlation of solar flares with the decay rate of radioactive isotopes [11, 12]. Solar flares are short (about 30 min) periods of increased electromagnetic activity of the Sun [13]. For such events X-ray radiation intensity in the energy range from 2 to 200 keV can increase by 4–5 orders of magnitude. Flares are divided into classes A, B, C, M, X in order of increasing intensity, for each subsequent class the intensity increases by one order of magnitude [8, 9]. Intensity of each flare expressed by corresponding numerical coefficient, for example X4.6. Average number of X class flares is about 20–30 per year during high solar activity periods, during period of solar minimum it tends to zero. They result in geomagnetic storms, radio communication disruptions and similar consequences. In addition, this X-ray radiation can damage satellite equipment and induce serious hazard to astronaut health [13]. At present, there are no reliable methods for predicting solar flares, therefore, development of new ones is of great practical importance.

For the first time, correlations between nuclear decay rate and intense solar flares were observed, probably, for the sequence of intense solar flares in December of 2006 [3, 11]. In this experiment the counting rate of γ ray produced in inverse β-decay of isotope ^{54}Mn was measured, γ rays with energy 980 keV produced in the decay were registered by scintillation detector. During the measurements significant long-term counting rate decreases correlated with solar flares were found. In particular, for X3.1 class flare of 13 December 2006, the decay rate decrease started 40 h before flare moment, and its minimum coincided in time with it, the rate deviation achieved at this minimum was about 3×10^{-3} of average decay rate [3]. In our previous experiments the semiconductor detectors were used for decay counting rate measurements in ^{60}Co β decay and in inverse β decay of ^{55}Fe. During the measurements in 2013–2020, four periods of significant decay rate decrease of ^{60}Co isotope decay rate at the level 10^{-2}–10^{-3} in comparison with its average values and two similar decrease periods for ^{55}Fe decays were found [12]. Such significant decreases began from 24 to 62 h before M flare moments, it indicates the possibility to predict such events basing on isotope decay rate values. In this paper the results of monitoring of ^{60}Co β-decay and ^{55}Fe decay rates in 2021–2024 and their correlations with solar activity in X-ray range are presented.

EXPERIMENTAL METHODOLOGY

In our setup exploited for ^{55}Fe decay parameter measurements γ-rays were registered by Si-PIN semiconductor detector cooled to 212°K in vacuum. Detector energy resolution is 200 eV, which allows to resolve main ^{55}Fe γ-ray spectral lines 5.9 and 6.5 keV. Detector sensitive area has a diameter 6 mm and separated from atmosphere by thin beryllium window. ^{55}Fe sample and detector contained in external thermostat which is stabilized at 293° K temperature. The distance between the sample and detector window is 5 mm. Registration threshold for γ-ray energy is 4 keV, all events with higher energy were recorded in computer memory. Background event rate was measured in separate runs once every three months and turned out to be practically constant at the level 39.1 ± 1.2 events per day in comparison to 6.5×10^7 registered decay events per day. The intensity and energy spectrum of background events evidence that main bulk of these events were stipulated by cosmic muons. Experimental setup sited in a brick building at a height of eight meters above ground level.

Coaxial high purity germanium detector of the H-type (HPGe) was used to register decay γ quanta produced in ^{60}Co decay with main spectral lines 1.173 and 1.332 MeV. Detector is cooled to 77.4 K, it is connected to standard spectrometric equipment and has a resolution of 1.8 keV for 1.173 MeV spectral line. The registration threshold for recording of γ-ray parameters was set at 100 keV; for such threshold the counting rate of background events was insignificant. This setup is located in a brick building basement. Detector sited in low-background lead chamber with wall thickness of 100 mm and internal copper screen to suppress secondary characteristic X-ray radiation. The distance between ^{55}Fe and ^{60}Co decay measurement setups was 3 km. Moscow time (MT) was used for data description; it is defined relative to universal time by formula MT = UTC + 3 h. Characteristics of solar flares were taken from the NASA catalog [15].

EXPERIMENTAL RESULTS

^{55}Fe decay statistics was recorded from October 20, 2021, to April 13, 2024, excluding interruptions caused by technical problems and calibration periods. ^{60}Co decay statistics was recorded from November 14, 2023, to March 7, 2024. On the average, observed γ-ray counting rates varied in accordance with expected exponential time dependence both for ^{55}Fe and ^{60}Co isotopes with 2.7- and 5.3-year lifetimes respectively [1]. During the current period of 11-year solar cycle, the solar activity was high, so it permitted to study decay counting rates correlations with X-class solar flares.

Collected statistics for ^{55}Fe decays allowed us to analyze decay correlations for eight X-class flare events. As the example of such correlation, Fig. 1 shows γ-ray counting rate difference from expected exponential dependence for the X1.1 class flare of October 2, 2022. Detector decay counting rate at this period on the average was 372 events per second. As follows from this plot, after exponential component subtraction, such deviation induces first the counting rate increase, which begins 150 h before flare moment, then at 96 h before it results in its significant decrease, observed maximum increase is about 0.4%, and maximal decrease is about 0.35%. For illustration, the value of expected average counting rate at the flare moment is added to obtained deviation values, in this case the rate is 374 events per second.

It should be noted that significant initial increase of decay counting rate was observed only for two solar events out of eight, for the rest of them it was small, as can be seen from Figs. 3 and 4. Therefore, for the main correlation characteristic, the observed counting rate decrease in comparison with expected decay rate was chosen. To calculate the probability of observed accidental counting rate deviation, the difference between expected event number N_e and observed number N_m during decrease period should be calculated. It assumed that systematic errors of decay counting rate are small and only statistical errors should be considered according to the Poisson distribution with statistical dispersion σ equal to square root of $N_e - N_m$ value in a given decrease period [1]. As the result, over 120 h

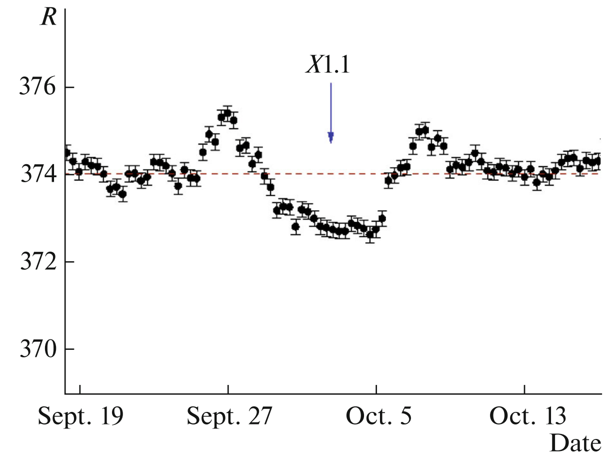

Fig. 1. Decay counting rate for ^{55}Fe decay from Septemmber 18, 2022 to October 17, 2022, the flare moment is marked by arrow.

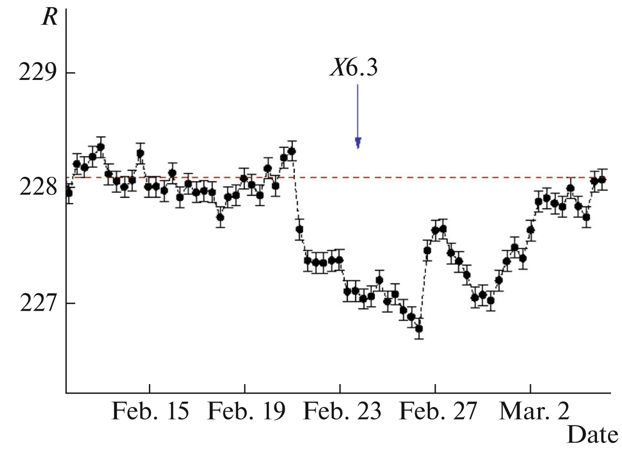

Fig. 2. Decay counting rate for ^{60}Co decay from Febuary 12, 2024 to Marxh 5, 2024, the flare moment is marked by arrow.

of decrease the total event difference $N_e - N_m$ is 705620, which corresponds to a statistical deviation E of 45.6 σ and probability of such random deviation is at the level 10^{-166}.

Table 1 shows the characteristics of ^{55}Fe counting rate deviation for X-class flare events. In addition to its statistical deviation, it includes the difference ΔT between the moment of rate deviation for 3σ and more and flare moment and its maximum deviation ΔI from expected rate during arbitrary 24 h. The same characteristics are used in Table 2 for deviations for ^{60}Co decay counting rate during solar flare events. Measurement errors for both decays are less than four hours for ΔT, and for ΔI errors are less than 0.01%.

For ^{60}Co decay correlations for solar flare events were registered, three X-class flares and one M-class flare with M7.2 intensity, their characteristics are shown in Table 2. Figure 2 shows decay counting rate deviation for solar flare of 23.02.2024 with intensity X6.6. This is maximum flare intensity over past six years. Detector counting rate during this period on the average was about 230 events per second. As can be seen from its plot, after subtracting the expected exponential dependence, this deviation first leads to counting rate increase, which began 85 h before flare moment, then 40 h before it results in significant decrease relative to its expected rate value, observed maximal reduction is about 0.45%. For illustration, expected counting rate for exponential dependence at the flare moment, which in that case is 228.1 events per second, added to it. The statistical effect of this deviation in the number of registered γ-ray events is 37.6σ, which corresponds to probability of random deviation at the level of 10^{-93}. It is notable that for all deviations of ^{55}Fe, ^{60}Co decay counting rate related to solar flares the probability of observed rate deviation is less than 10^{-12}.

It is important to note that two X-class flare events were registered simultaneously, both by ^{55}Fe and ^{60}Co decay counting rates, their joint plots are shown at Figs. 3 and 4 in relative units. Average counting rate for ^{60}Co decays during this period was about 230 events per second, and for ^{55}Fe decays—about 340 events per second. These plots demonstrate that significant counting rate deviations began approximately 36 h before flare moments for both decay types. Such joint registration of correlations for both setups increases

Table 1. ^{55}Fe decay rate deviations near solar flare event moments

Date	Flare intensity	ΔT, h	ΔI, %	$E(\sigma)$
Oct. 28, 2021	X1.0	128	.18	9.5
Apr. 17, 2022	X1.2	116	.43	44.1
Oct. 2, 2022	X1.1	150	.35	45.6
Jan. 6, 2023	X1.1	56	.17	23.3
Dec. 14, 2023	X2.7	36	.11	8.1
Jan. 1, 2024	X4.8	124	.15	12.4
Mar. 23, 2024	X1.1	32	.13	17.1
Mar. 29, 2024	X1.2	80	.14	28.2

Table 2. ^{60}Co decay rate deviations near solar flare event moments

Date	Flare intensity	ΔT, h	ΔI, %	$E(\sigma)$
Dec. 14, 2023	X2.7	72	.85	89.1
Jan. 1, 2024	X4.8	142	.42	45.6
Jan. 29, 2024	M7.2	140	.33	34.7
Feb. 23, 2024	X6.6	64	.38	37.6

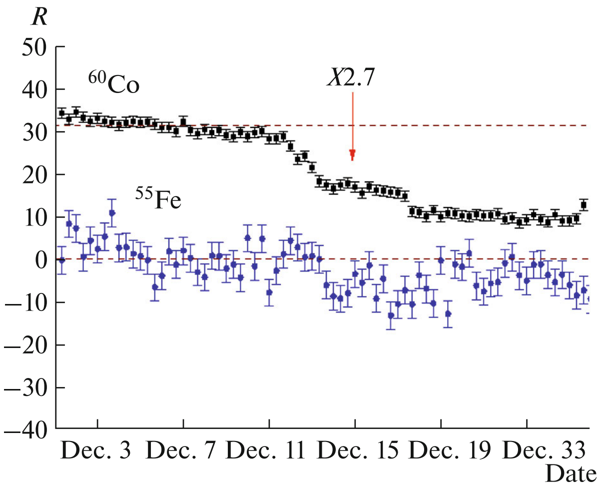

Fig. 3. Decay counting rates for ^{55}Fe and ^{60}Co decays from December 1, 2023 to December 25, 2023, the flare is moment is marked by arrow.

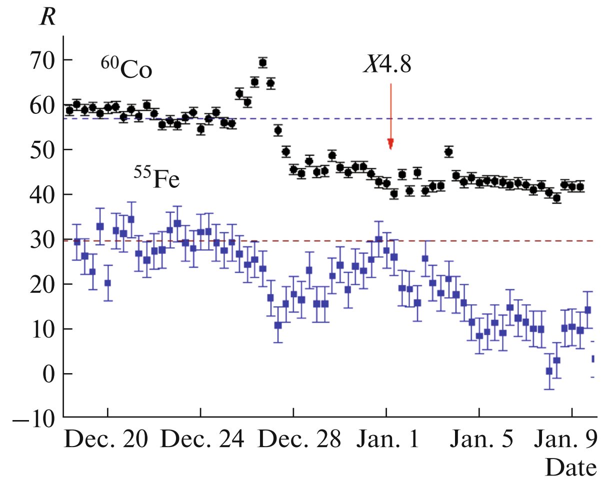

Fig. 4. Decay counting rates for ^{55}Fe and ^{60}Co decays from December 19, 2023 to January 9, 2024, the flare moment is marked by arrow.

reliability of studied effect existence, it reduces probability of any systematic factor presence, which can influence detector performance. It is also important to note that during the measurement period, the counting rate of ^{55}Fe decays—about six years, and ^{60}Co—about five months, no significant counting rate deviations unrelated to solar flare events were registered.

CONCLUSIONS

Presented experimental results, along with those published previously [12], demonstrate advanced time correlations between statistics of ^{55}Fe, ^{60}Co weak decays and intense solar flares, meanwhile, the origin of such influence is currently unknown. It is well known that solar flares generate electromagnetic radiation in wide frequency range [8], correspondingly, such radiation can have various effects on terrestrial objects, including changes of the Earth's magnetic field and possible voltage surges in electric networks.

Thus, it could be assumed that the observed deviations in the counting rate in ^{55}Fe, ^{60}Co decays could arise due to the reaction of our gamma-ray detection systems not directly to the solar flares, but to the external effects caused by them. The most convincing argument against such explanation of obtained results is that almost for all analyzed events the decay counting rate began to decrease more than a day before the moment when the flare was registered by the equipment installed on satellites. Since it seems unlikely that any other type of electromagnetic radiation from solar flare can reach the Earth significantly earlier than gamma-rays, any explanation of the data obtained for ^{55}Fe and ^{60}Co decays as consequence of ordinary electromagnetic radiation influence from the Sun during solar flare can be excluded. In particular, the most significant effect on geomagnetic field of the Earth occurs with the arrival of a flux of charged particles emitted by the Sun during flare, but this flux, on average, reaches the Earth two days after the registration of γ-ray from the flare by satellite instruments [10]. Considering the possible influence of randomly fluctuating external magnetic fields on our detector systems, it should be noted that their only sensitive elements are semiconductor detectors, but their characteristics do not change even in magnetic fields in the range of up to several Tesla [1].

Meanwhile, measurements carried out for weak decays of some nuclei in other experiments did not reveal noticeable time correlations of decay parameters with solar flares [16–19]. It should be noted, however, that the conditions of these experiments differed significantly from those we used. First, a significant part of the experiments were conducted in an underground laboratory at the depth of about 2 km, in particular, this was so for the only experiment in which semiconductor detector was used [16]. At the same time, it is impossible to exclude the screening of this factor of solar influence by such rock layer. In the ground experiments, only scintillation detectors were used; perhaps, this technique is less sensitive to the effects under study. Meanwhile, due to the extremely important practical significance of predicting solar flares, it seems reasonable to continue such studies for various isotopes and detection techniques. It should be recalled that during inverse β decay of the ^{55}Fe nucleus, an electron from the L- or K-shell is captured by the nucleus and an electron neutrino is emitted, after which an electron from the upper shell of the atom occupies a free vacancy in the K- or L-shell. As the result, γ-ray can be emitted as a result of such a transition, compensating transition energy. During ^{55}Fe decay, γ rays with an energy of 5.9 and 6.5 keV are emitted with a probability of 25 and 3.4%, respectively. As the result, the total probability of the decay of ^{55}Fe with emission of a gamma ray is 28.5%, the remaining decay channels generate Auger electrons that are not registered by standard gamma-ray detectors. Consequently, for this type of decay, hypothetical external influence can be identified, even if it does not affect the lifetime of the nuclei, but rather the change in the probability of decay modes. It should also be noted that for ^{55}Fe decay the energy difference between nuclear initial and final states is at least two orders of magnitude smaller than for other weak decays used to study the correlations of their parameters with solar activity. As the result, this decay may be more sensitive to some factors of such solar influence.

This paper presents results that demonstrate with a high degree of reliability the existence of correlations between the decay rates of the isotopes ^{55}Fe, ^{60}Co and solar activity. The possible nature of such correlations is unclear, and the models proposed so far do not look convincing [3, 8]. However, it cannot be completely ruled out that some particles or fields (possibly unknown) generated by the Sun can affect the decay rate of unstable nucleus. In addition, the nature of solar activity is poorly understood, and studying its influence on nuclear decays can provide additional information on that as well [13]. In total, the measurements of the ^{55}Fe decay rate conducted during 2017–2024 cover transition period from the Sun transition to the minimum of the solar cycle at the end of 2019 to its maximum observed since 2023. At the same time, for ^{55}Fe decay counting rate from mid-2017 to the end of 2018, long-term decreases at a level of up to 5% were observed for two periods of approximately two-month length [12].

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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