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Search of x-ray solar activity correlations with ^{55}Fe , ^{60}Co nucleus decay rates

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Abstract. Several experimental groups observed temporary modulations of some nuclei strong and weak decay constants, which are of the order of 10^{-3} and with periods of one year, solar day, i.e. 24 hours and some others. In our experiments the decay rates were measured for ^{55}Fe e -capture and ^{60}Co β -decay during 2012–2020. Altogether, six decay rate dips of the order $10^{-2} - 10^{-3}$ and with duration from 40 to 208 hours were found, they deviate essentially from exponential decay rate fit. It is shown that their occurrence correlate with x-ray solar flares with significant reliability. Besides, two long term deviations of ^{55}Fe decay rate of 62 and 41 days were observed in 2017–2018, it's argued that they are related to the change of 11 year solar cycle stages.

1. Introduction

It is universally acknowledged that the radioactive nuclei decay parameters are time-independent and practically no environmental influence can change them [1]. However, some recent experiments have reported the evidence of time modulations of nuclei α - and β -decay constants of the order of 10^{-3} and with periods of one year, one day or several months [2–4]. In brief, published results can be summarized as follows: the main bulk of them reports the annual sinusoidal oscillations of β -decay rate of different heavy nuclei, from Si to Ra, for most of them the oscillation amplitude is approximately 5×10^{-4} 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. We note that some other experiments exclude annual β -decay constant modulations as large as reported ones [7, 8]. Theoretical models proposed to explain such effects are discussed in [3, 9].

Other studies in this field discuss a possible influence of solar activity on the nuclear decay parameters, in particular, the correlations of solar flares with nuclear decay rates. Solar flares are periods of increased solar activity in particular, of solar x-ray emission rise [10, 11], and are often associated with geomagnetic storms, radio blackouts, power surges in electric grids, and other similar effects that are experienced here on Earth. Hence their reliable prediction will be important to reduce the damage from these phenomena, besides, it can also improve



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the radiation safety of long-term space missions. Flare correlations with nucleus decay rate presumably were observed for the sequence of intensive solar flares and coronal mass ejections (CME) in December 2006 [3, 12]. During this period, e -capture process was monitored for ^{54}Mn sample, and, altogether, three decay rate dips were detected, two of them correlated with solar flares, one with severe CME [11]. In particular, for X3 class flare 13 December 2006, the decay rate decrease started 40 hours 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. Meanwhile, the measurements performed with some other nuclear decay modes did not reveal any sizable correlations of their rate with the solar flares [13, 14]. However, due to the utmost practical importance of solar flare predictions, it seems reasonable to continue these studies with available nuclear decays and detectors. We remind that solar flares are classified according to their amplitudes from minimal to maximal as A, B, C, M, X, which differ from one to another by one order of x-ray intensity. Average number of M and X flares is about 10 per year, during period of solar minimum it tends to zero [10].

This paper describes the studies of correlations of x-ray solar activity with ^{55}Fe e -capture rate during 2017-2020 and with ^{60}Co β -decay rate during 2012-2016. We remind that in e -capture decay mode, L - or K -electron is captured by nucleus, electron neutrino is emitted, after that electron from the upper shell occupies the free vacancy on K or L -shell. As the result, soft γ -quanta can be emitted during such a transition. For ^{55}Fe electron capture γ -quanta with energies 5.9 and 6.5 keV are emitted with the probability 25% and 3.4% correspondingly. The important distinction of ^{55}Fe decay is quite small energy difference between initial and final nucleus states, this is at least two orders less than in other decays exploited up to now for the studies of solar activity correlations. Besides, the total ^{55}Fe branching of γ -quanta decay channels is 28.5%, the rest is the decay into Auger electrons, undetectable for standard γ -ray detectors. Hence for such a decay the hypothetical external force can be identified even if it influences not on nuclei life-time, but on the channel branching as well. ^{60}Co β -decay is accompanied by γ -ray emission lines with energies 1332.5 keV and 1173.2 keV which has approximately equal branching close to 100% .

2. Experimental Performance

In our set-up for ^{55}Fe decay rate measurement, γ -quanta detection is performed by Si-PIN photodiode detector cooled to the temperature -55°C . The detector energy resolution FWHM is 180 eV, that permits to resolve effectively two ^{55}Fe spectral lines. The photodiode sensitive region has a diameter 6 mm and is shielded by thin beryllium window. The source and detector are confined in metal thermostat, within it the constant temperature 20°C , which was conserved during the measurements with the precision up to 0.2° . Detector amplifier is integrated inside the detector volume, its input transistor cooled together with the photodiode. Experimental set-up was installed in laboratory 10 meters higher the ground level, ^{55}Fe sample was located at the distance 5 mm from the photodiode surface. After two years of exploitation the sample was replaced by new one with the same initial activity.

During the measurement runs the discrimination threshold of 3 keV was imposed on the detector pulses, all pulses with higher energy were recorded for off-line analysis. After the selection of events which can be ascribed by 5.9, 6.5 keV peaks the detector counting rate was about 10^2 events/sec. Background detector counting rate was measured in the separate runs every month and found to be practically constant with the rate of 39.1 ± 1.2 events per day, in comparison with 9.3×10^6 decay events per day. Both rate and amplitude spectra is compatible with hypothesis that the main bulk of background events owed to cosmic muons traversing the silicon crystal.

Coaxial High Purity germanium detector (HPGe) of N-type GMX25-70-A was used for detection of γ -rays from ^{60}Co decay, it operates at cryogenic temperature 85°K and was mounted

at ground level. The detector was connected to the spectrometric station, which transfers data to the computer. Detector energy resolution FWHM is about 5 keV, average counting rate is about 20 events/s, background rate in 1 MeV energy range is found to be negligible.

3. Experimental results

^{55}Fe decay statistics was collected from 3 March 2017 to 30 September 2020 with several short breaks induced by technical problems. ^{60}Co decay statistics was collected from 14 September 2012 till 29 December 2016 with some breaks also. On the average, observed decay rates decreased monotonously in accordance with expected for ^{55}Fe and ^{60}Co life-time decay exponents. Study of possible periodic decay rate variations still continues and will be published later.

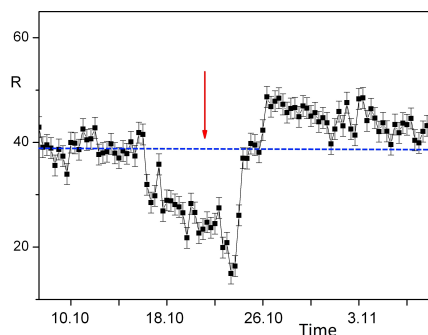


Figure 1. Reduced ^{55}Fe decay rate per 30 sec for 09.10–08.11.2017, dashed line is life-time exponent fit, flare moment marked by red arrow.

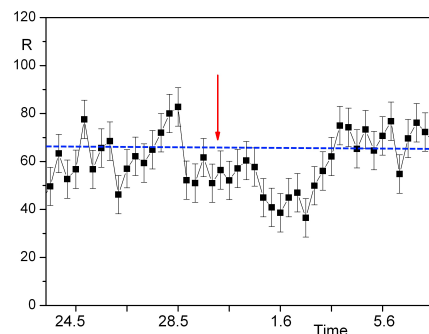


Figure 2. Reduced ^{55}Fe decay rate per 30 sec for 23.05–07.06.2020, dashed line is life-time exponent fit, flare moment marked by red arrow.

Two significant local deviations from ^{55}Fe decay exponent which can be associated with the solar flares were found. First one constitutes the abrupt reduction for $7.9 \cdot 10^{-3}$ of detector counting rate, it has started 17 October 2017 at 4:00 (all time data are UT) and ended 25 October 2017 at 20:00. If we subtract the corresponding exponential fit, then for resulting reduced rate this dip acquires nearly rectangular form as shown on figure 1. It supposedly correlates with M1.1 solar flare which occurred 20 October 2017 at 23.10 [15]. We have considered whether the coincident fluctuations in decay rate data and solar flare data for this event could simply arise from statistical fluctuations in each data set. We have defined the dip region in the decay data as 208 hours, the measured number of decays N_m in this region can be compared with to the number of events expected in the absence of observed fluctuations, assuming a monotonous exponential decrease in the counting rate. Since we expect that the systematic errors in N_e , N_m are small, only statistical errors are retained, and we find,

$$N_e - N_m = (35.8 \pm 1.4) \cdot 10^4 \quad (1)$$

where the dominant contributions to the overall uncertainties arise from \sqrt{N} fluctuations in the counting rates. If we interpret equation (1) in the conventional manner as 25σ effect, then the formal probability of such fluctuation in 208 hours interval is $P_s = 3.7 \cdot 10^{-98}$. Evidently, even including the additional small systematic errors would not alter the conclusion that the observed fluctuation on 17–25 October 2017 is not likely a purely statistical effect. Note that this flare was last M class one of 24 solar 11 year cycle.

Table 1. Parameters of decay rate dips.

I	Date	A	ΔT , h	E , σ
^{55}Fe	20.10.2017	M1.2	84	25
^{55}Fe	29.05.2020	M1.1	40	12.5
^{60}Co	28.11.2012	M7.2	24	16
^{60}Co	22.04.2013	M1.1	12	14
^{60}Co	07.06.2013	M5.9	56	31
^{60}Co	28.11.2016	M1.1	50	32.5

First M class flare of next 25 solar cycle classified as M1.1 has occurred on 07:11, 29 May 2020. It correlates with 130 hour ^{55}Fe decay rate dip shown on figure 2, after exponential fit subtraction the form of resulting reduced rate becomes similar to the considered rate dip of October 2017. In particular, in both cases the decay rate falls promptly, less than for 8 hours, also both decay rates reduced additionally after the flare moment. However, the relative rate reduction is significantly less than in previous case of October 2017 which supposedly can be explained by the fact that the solar dark spot which emitted x-rays was located on the edge of solar disk. Statistical analysis analogous to the one performed for October 2017 event describes it as 12.5σ effect which gives $P_s = 2.8 \cdot 10^{-33}$. It's notable that during 1289 days of ^{55}Fe data acquisition no other dips of similar duration and rate decline were found.

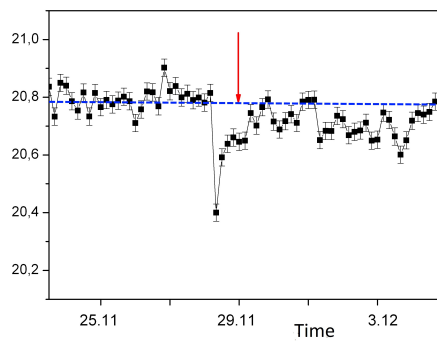


Figure 3. ^{60}Co decay rate for 23.11–05.12.2012, dashed line is life-time exponent fit, flare moment marked by red arrow.

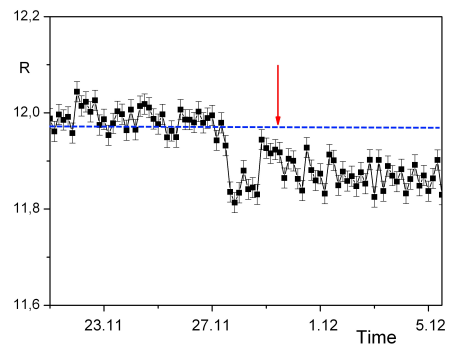


Figure 4. ^{60}Co decay rate for 21.11–05.12.2016, dashed line is life-time exponent fit, flare moment marked by red arrow.

Four decay rate dips which can be associated with solar flares were found for ^{60}Co β -decay in the data recorded in 2012–2016, their parameters summarized in table 1. Their plots are shown in figures 3-6, where the decay rate is averaged over two γ lines, so that the real detector counting rate is two times larger. In table 1 A denotes flare intensity, ΔT is the estimated time interval between the dip forward front and flare moment, E is statistical effect in σ units. For example, the rate deviation correlated with M7.2 flare, shown on figure 3, has $E = 16\sigma$ which corresponds to the probability $P_s = 1.8 \cdot 10^{-59}$. Altogether, as shows table 1, both for ^{55}Fe and ^{60}Co , the correlation of decay rate dips and intense solar flares is perfectly proved statistically and practically exclude its stochastic character, but possible systematic errors still

need additional investigation.

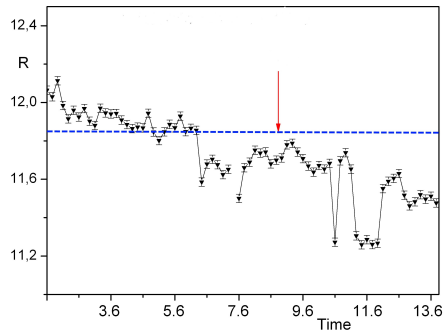


Figure 5. ^{60}Co decay rate for 01.06–13.06.2013, dashed line is life-time exponent fit, flare moment marked by red arrow.

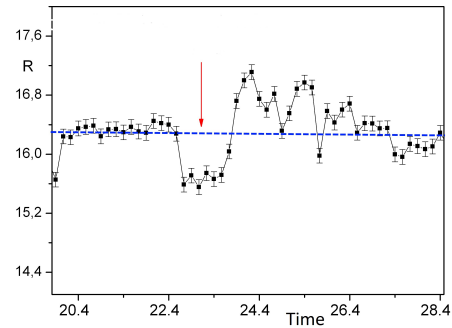


Figure 6. ^{60}Co decay rate for 19.04–28.04.2013, dashed line is life-time exponent fit, flare moment marked by red arrow.

Deviation of principally different type, shown on figure 7, was observed during July–September 2017. In this case, ^{55}Fe detector counting rate demonstrates steep decline for $3.1 \cdot 10^{-2}$ from 6 to 12 July, another decline for $.9 \cdot 10^{-2}$ occurred from 26 to 30 July. If to subtract exponential fit, then this dip was nearly constant till 30 August when decay rate starts to rise steeply till 7 September, after that the standard exponential decline resumed. Comparison with the flare events reveals that three M class flares occurred 3, 9, and 14 July, i.e. presumably correlated with decay rate decline period. Two X class flares occurred 6 and 10 September and thus correlate with the decay rate rise, in addition, one more M class flare has occurred 20 August, i.e. just preceding the rate rise. It's notable that the flare of 6 September was the most intense solar flare of 24 cycle achieving amplitude of X9.2. In addition, the severe CME with very large proton velocity occurred 23 July and presumably was correlated with observed intermediate dip. Another long term ^{55}Fe decay rate deviation was observed from 3 October to 13 November 2018 approximately, it is shown on figure 8. In that case, ^{55}Fe decay rate variation possesses nearly sinusoidal form, it deviates more slowly and its maximal dip constitutes $3 \cdot 10^{-2}$ of initial rate. Note that sizable oscillating deviations from exponential fit continued till the end of 2018. The statistical errors for both these long-term deviations is infinitesimally small; possible relation of these deviations to solar cycle are considered in the final section.

4. Discussion

As was stated before, solar flares are known to produce a variety of electromagnetic effects on Earth, including changes in Earth's magnetic field and power surges in electric grid. It is thus conceivable that the observed dips in the ^{55}Fe , ^{60}Co counting rate could have arisen from the response of our detection system (rather than the sample atoms themselves) to the solar flare. The most compelling argument against this explanation for ^{55}Fe data is that ^{55}Fe decay rate in October 2017 and May 2020 began to decrease more than two days before any signal was detected in x-rays by the GOES satellites. Since it is unlikely that any other electromagnetic signal would reach the Earth earlier than the x-rays, we can reasonably exclude any explanation of the ^{55}Fe data in terms of a conventional electromagnetic effect arising from the solar flare. This is particularly true since the most significant impact on the geomagnetic field occurs with the arrival of the charged particle flux, several hours after the arrival of the x-rays. We can further strengthen the preceding argument by examining in detail the response of our detection

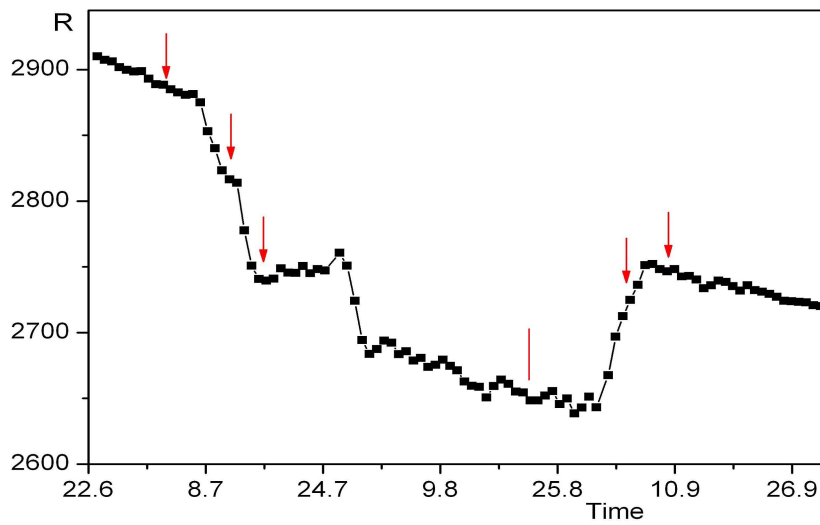


Figure 7. ^{55}Fe decay rate per 30 sec for 22.06–30.09.2017, flare moments marked by red arrows, rate errors are less than point size.

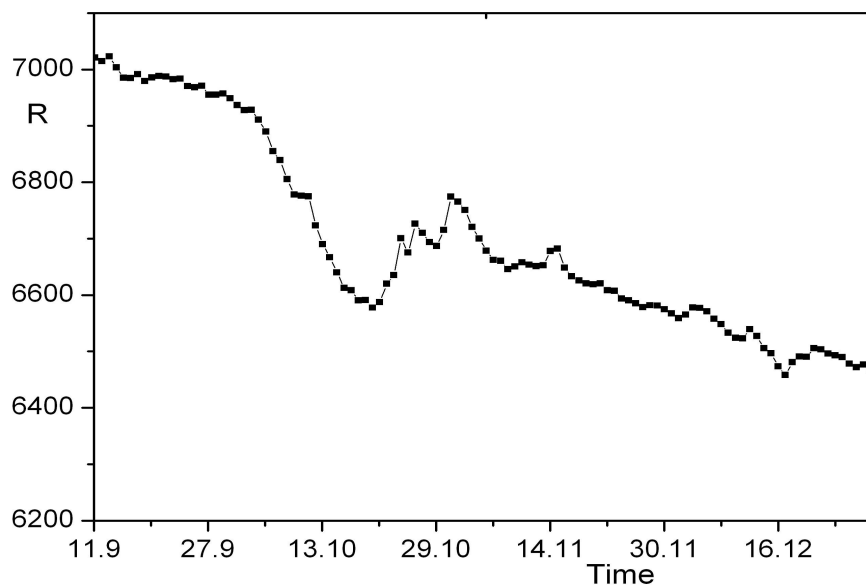


Figure 8. ^{55}Fe decay rate per 30 s for 11.09–30.12.2018, rate errors are less than point size.

system to the fluctuations in line voltages. No unusual behavior was detected by either the Moscow electric energy company which supplies power to our lab. In our lab, an alert would have been triggered if the line voltage strayed out of the range 210–230 V, and hence we can infer that the voltage remained within this range during the solar flare. Moreover, since the main effect of a power surge would have been to shift the ^{55}Fe peak slightly out of the nominal region of interest (ROI) for the 5.9 and 6.5 keV X-ray, this would have been noted and corrected for in the routine course of our data acquisition. No significant changes to either the peak shapes or locations were found during this period. We turn next to an examination of the effect of fluctuating external magnetic fields on our detector systems. Its only sensitive element is semiconductor detector, however, its performance does not change even in the magnetic fields of Tesla range [1]. The analogous arguments can be given for ^{60}Co decay rate measurement data, due to their similarity, we omit them here.

In this paper new results are presented, which presumably demonstrate the correlation between ^{55}Fe , ^{60}Co isotope decay rates and some forms of solar activity. The possible nature of such correlations is quite obscure, the models proposed up to now are not convincing [3, 12]. However, it can not be excluded completely that some particles or fields (may be unknown) generated by the Sun would influence the nucleus decay rates. Besides, the mechanism of solar activity variation by itself is quite poorly understood and study of it influence on nuclear decay can shed the new light on it also. In particular, 11 year cycle of solar activity is a well established fact, but there is no solid theory of its origin and performance [10]. Our decay measurements during 2017–2020 encompass the transition period from active to quiet cycle stages and back. The significant ^{55}Fe decay rate deviations from 7 July to 6 September 2017 and from 3 October to 13 November 2018 shown on figures 7–8 supposedly indicate that such transition is complex, multistage process, in which these periods play the special, important roles. They are associated, probably, with transition to reduced solar activity stage, because no X-class solar flares were detected after 10 September 2017 during more than three years, the rate deviation of October–November 2018 preceded the absolute minimum of solar activity in February–December 2019.

Acknowledgments

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