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No correlation between Solar flares and the decay rate of several β-decaying isotopes

J.R. Angevaare[a], P. Barrow[b], L. Baudis[b], P.A. Breur[a,*], A. Brown[b], A.P. Colijn[a], G. Cox[c], M. Gienal[b], F. Gjaltema[a], A. Helmling-Cornell[c], M. Jones[c], A. Kish[b], M. Kurz[b], R.F. Lang[c], A. Massafferri[d], J.C.P.Y. Nobelen[a,*], R. Perci[d], C. Reuter[c], D. Schenk[a], M. Schumann[e]

[a] *Nikhef and the University of Amsterdam, Science Park, 1098 XG Amsterdam, the Netherlands*
[b] *Physik-Institut, Universität Zürich, 8057 Zurich, Switzerland*
[c] *Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA*
[d] *Centro Brasileiro de Pesquias Físicas - COHEP, R. Dr. Xavier Sigaud, 150 - Urca, Rio de Janeiro, Brazil*
[e] *Physikalisches Institut, Universität Freiburg, 79104 Freiburg, Germany*

Abstract

We report on finding no correlation between the two strongest observed Solar flares in September 2017 and the decay rate of ^{60}Co, ^{44}Ti and ^{137}Cs sources, which are continuously measured by two independent NaI(Tl) detector setups. Over multiple periods of timescales varying from 1 to 109 hours around the Solar flare we test for variations in the number of observed counts with respect to the number of expected counts. No excess or deficit is observed to exceed the 2σ global significance. For an 84-hour period around multiple Solar flares in December 2006, a $\sim 0.01\%$ deficit in decay rate of ^{54}Mn was reported with 7σ significance by Jenkins and Fischbasch [2]. We set a conservative lower limit over an 84-hour period around the two correlated Solar flares in September 2017 to 0.044% with 2σ confidence. We thus see no correlation and observe no effect such as the reported one by Jenkins and Fischbach [2].

1. Introduction

In the past decade, various claims [1–4] were made that the decay constant of isotopes decaying through β-emission is influenced by Solar neutrinos. All claims focus on a deficit in decay rate as a function of neutrino flux in two ways: firstly, an annual modulation in the decay rate [1] is claimed, which is hypothesised to depend on the change in Solar neutrino flux on Earth. Secondly, it is claimed that neutrinos created at the Sun's atmosphere during a Solar flare cause a short-term deficit in the radioactive

*Corresponding Author
Email addresses: sanderb@nikhef.nl (P.A. Breur), jaspern@nikhef.nl (J.C.P.Y. Nobelen)

decay rate [2]. In this article, we report on the latter effect.

The authors of [2] correlate an X-ray emission peak from a Solar flare of $3.4 \cdot 10^{-4}$ W/m^2 (classified as X3.4) along with other peaks in the X-ray flux as measured by the Geostationary Operational Environmental Satellite (GOES) with a deficit in the radioactive decay rate of a $\sim$1 μCi ^{54}Mn source over the month of December 2006. In their study, the ^{54}Mn sample was attached to the front of 2 $\times$ 2" NaI(Tl) crystal detector. The number of observed counts was summed over a period of 84 hours and found a deficit of 7σ significance in the decay rate. During the same flares as used in [2], a different setup monitored the decay of the isotopes ^{90}Sr, ^{90}Y and ^{60}Co using a Geiger-Müller counter and a ^{239}Pu source using a silicon detector [5]. No significant deficit in the radioactive decay rate was found for these isotopes. Another study measured a ^{137}Cs source with a HPGe detector and on a ^{40}K and a ^{nat}Th source with a NaI(Tl) detector and correlated Solar flares of strength X5.4 and X6.9 during 2011 and 2012 [6]. Over a 24-hour period, no effect was observed and the authors set a limit on the relative deviation in the decay rate to a few 0.01%.

On the Sun's photosphere darker spots, known as sunspots, may appear under the influence of strong magnetic fields. During a Solar flare, magnetic field lines at sunspots reconnect [7, 8] and convert magnetic energy into kinetic energy of the plasma. The heated plasma yields a strong X-ray emission and is capable of accelerating protons and electrons up to hundreds of MeVs. The typical timescale for a Solar flare is in the order of minutes [14]. Solar flares are assumed to increase the Solar neutrino flux in two ways [9, 10]: a short-timescale increase in neutrino flux, directly created during the Solar flare and a delayed increase in flux due to the interaction of accelerated flare particles with the Earth's atmosphere. Neutrino flux experiments have not yet found a direct correlation between Solar flares and an increase in neutrino flux [11–13].

On September 6th 2017, 12:02 UTC, the GOES-13 Satellite observed a peak of $9.3 \cdot 10^{-4}$ W/m^2 in X-ray flux [15, 16]. This flare was classified as an X9.3 flare. Four days later, on September 10th, 16:06 UTC, a second X8.2 flare was observed by the GOES-13 Satellite [15, 16]. Both these flares shared stronger X-ray emissions than the X3.4 Solar flare of December 13, 2006.

In this work paper, we present data for the month of September 2017, measured by two identical, independent NaI(Tl) detectors. The complete detector setups are discussed in detail in [17]. Each of the setups contain 4 cylindrical (76$\times$76)mm NaI(Tl) detector pairs. Three of the four detector pairs measure the decay of a specific radioactive isotope each, while the remaining pair monitors the radioactive background. We extract al decay rates by using a fitting routine which obtains the number of counts inside the full absorption peak [17]. The remaining two identical setups located at the CBPF, Rio de Janeiro, Brazil and at Purdue University, USA did not take data in September 2017. The length of a bin is set to 1 hour.

An overview of all correlations can be found in the first three columns of Table 1. We correlate the X9.3 Solar flare of September 6th with the decay rate of a $\sim$0.5 kBq ^{60}Co source, continuously measured by two independent, identical detector setups located at

Universität Zürich (UZH), Switzerland and at Nikhef Amsterdam, the Netherlands. Secondly, we correlate this X9.3 flare with the decay rate of two ∼0.8 kBq sources, ^{44}Ti and ^{137}Cs, measured by the detector setup at Nikhef. Lastly, we correlate the decay of the ^{60}Co source monitored by the UZH setup to a second (X8.2) flare of September 10th. The ^{54}Mn and ^{44}Ti sources monitored by the UZH detector are not used in this analysis due to too low statistics and saturation of the detector at high energies, respectively.

2. Methodology

We correlate the two Solar flares, characterized by their X-ray emission, with the decay rate of ^{60}Co, ^{44}Ti and ^{137}Cs sources using three different statistical tests. Because there is no proposed Solar flare mechanism determining the size or duration of a possible deficit in the decay rate, we test over different periods around the time of the Solar flare event, with timescales between 1 and 109 hours. The maximum period is chosen such that it encompasses the reported 84 hours by [2] plus one day. The Solar flare periods are defined as follows: the first period consists of the one-hour bin coinciding with one of the two Solar flares. From here, the Solar flare periods are increased symmetrically per bin. For every period, we calculate the relative deviation (see Section 2.1). Additionally, we calculate the probability of measuring the observed number of counts with respect to the expected number of counts (see Section 2.2). Specifically over the reported period of 84 hours [2], we then set a limit (Section **??**) on the relative deviation of the decay rate. We also perform two other tests (see Section 2.3), to check the normality of the data set and to test the hypothesis stated by [2]. Therefore the first is a Shapiro-Wilk (SW) normality test [20], the second a one-tailed deficit test [18].

2.1. Relative Deviation

To calculate a variation with respect to the expected number of counts, we first perform an exponential fit to the observed number of decays. To prevent bias, we exclude the maximum considered timescale of 109 hours from the fitted exponential decay,

$$A(t) = A_0 \cdot 2^{-t/t_{1/2}}, \tag{1}$$

where t is the time, A_0 the activity of the isotope at $t = 0$ (midnight on September 1st UTC) and $t_{1/2}$ the half life of the isotope. We define a unitless relative deviation in the number of counts per period as

$$\Delta N_i = \frac{\sum_{j=1}^{m} (N_{obs}) - \mu_i}{\mu_i}, \tag{2}$$

where we define $\mu_i = \int_{t_{i,min}}^{t_{i,max}} A(t)dt$ with $t_{i,min}$ and $t_{i,max}$ the beginning and ending of each period i around the flare. The amount of observed counts N_{obs} is summed over m bins around the flare. The result of equation (2) is shown in Figure 2 and correspond to the blue data points .

2.2. Two-tailed variation test

Because we do not have any proposed Solar flare mechanism that influences the size or duration of the deficit in decay rate, we test for two-tailed variations [18] in the number of observed counts N_{obs} with respect to the number of expected counts μ over multiple flare periods and calculate the Poisson probability of finding a more extreme number than N_{obs}. The local test statistic is defined as

$$q = \begin{cases} 2F(N_{obs}, \mu) & \text{if } N_{obs} < \mu \\ 2[1 - F(N_{obs}, \mu)] & \text{if } N_{obs} > \mu \ , \end{cases} \tag{3}$$

$$\text{and} \lim_{N_{obs} \to \infty} (F(N_{obs}, \mu) \sim \Phi(\mu, \sigma = \sqrt{\mu}))$$

where $F(N_{obs}, \mu)$ is the cumulative distribution function (CDF) of the Poisson distribution which is approximated by the CDF of a Normal distribution Φ for large values of N_{obs}. To correct for performing tests on multiple periods at the same time, also known as the Look-Elsewhere Effect [19], a global significance is required. To find this global significance, the following procedure is followed: first, we create a new data set from a Monte Carlo (MC) simulation which draws points from a Poisson distribution following the null hypothesis, i.e. exponential decay (described by equation 1). This MC runs over a total of 30000 trials, chosen in order to get at least 2 sigma confidence. Subsequently, we perform the same two-tailed variations test (equation 3) over the same flare timescales between 1 and 109 hours. For each trial, we define the new test statistic as

$$\widetilde{q} = \min_{i}^{N}(q), \tag{4}$$

where i and N are the number of performed two-tailed variations tests and q is the test statistic found by equation (3). As a result we obtain 30000 new $\widetilde{q}$-values and from the cumulative distribution function (CDF) of $\widetilde{q}$, a local p-value is translated to a global p-value. Using this new global p-value, we calculate an extreme number of observed counts ($N_{obs \to extreme}$) given the expected number of counts μ and the significance level. The 1σ (blue) and 2σ (green) bands in Figure 2 are the confidence intervals (CI) found by transforming $N_{obs \to extreme}$ into a relative deviation with equation (2). If all points are within the global CI, we conclude that over every tested timescale our data follows exponential decay within the chosen significance level, as defined by equation (1).

2.3. Shapiro-Wilk and one-tailed deficit test

To test the normality of the data set, a Shapiro-Wilk test [20] is performed on the normalized residuals of a 84-hour period around the Solar flare. It has been shown through simulations that, for large samples, the Shapiro-Wilk test is most powerful in correctly rejecting the hypothesis that a sample is normally distributed [21]. If the tested sample is consistent with a normal distribution, we conclude that any observed fluctuations are consistent within bounds expected from statistical uncertainty.

Finally we test the hypothesis claimed by [2] that a Solar flare causes a decrease in rate, by performing a one-tailed deficit test on the decay rate over a period of 84 hours. In the one-tailed deficit test [18], we test for the chance of finding a number of observed

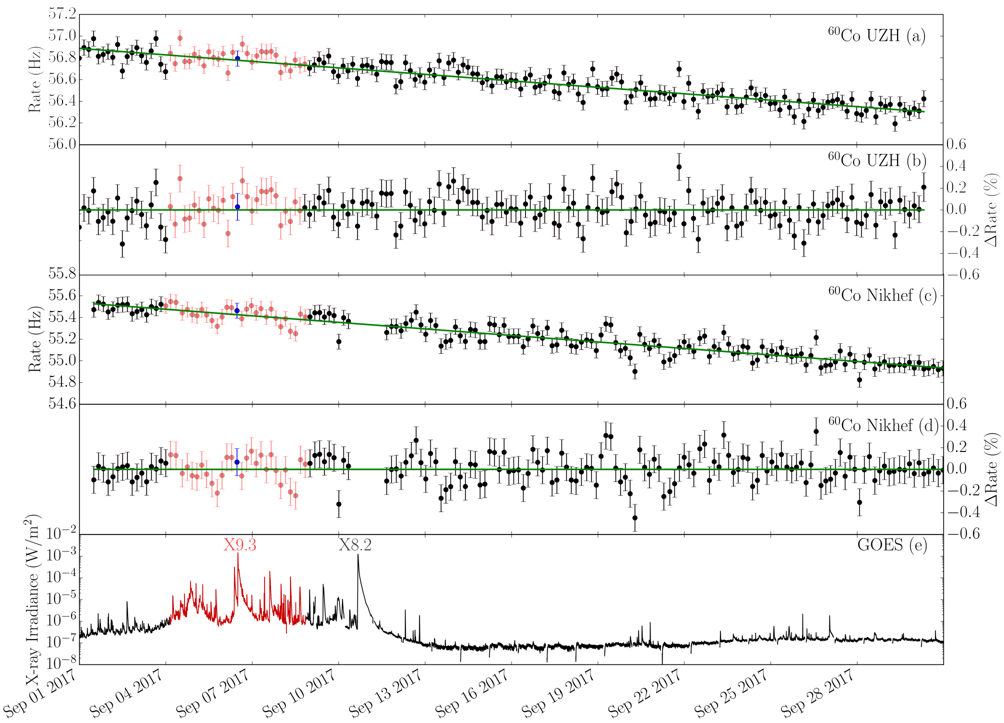

Figure 1: The measured count rate for ^{60}Co decays, presented in 4 hour bins, measured by the NaI(Tl) detector setup at UZH (a) and Nikhef (c). The X-ray flux in W/m^2 is shown (e), as measured by the GOES Satellite [15] during September 2017 is shown.The X9.3 Solar flare of September 6th 2017 is coincident with the blue bin. The data points of the 109 hour period around the flare (red) are excluded from the exponential fit (green) which is used to determine the residuals (c & d for the UZH and Nikhef NaI(Tl) setups, respectively). The same procedure is followed for the analysis of X8.2 Solar flare.

counts more extreme than the observed number of counts, assuming the expected number of counts is normally distributed. If the tested sample is not consistent with a deficit, we reject the hypothesis claimed by [2].

3. Results

Figure 1 shows the measured decay rate of ^{60}Co over the month of September 2017, as measured by the setup at UZH (a & b) and at Nikhef (c & d). The X-ray flux including the X9.3 and X8.2 Solar flares is shown (e), as measured by the GOES-13 satellite [15]. The detector setup at Nikhef did not collect any data between September 10th, 11:37 UTC and September 11th, 10:59 UTC due to a data storage error. We therefore cannot correlate our Nikhef data to the second X8.2 Solar flare. The X9.3 Solar flare of September 6th is coincident with the blue data point. The red data points define the maximum test Solar flare period of 109 hours, which includes the 84 hour period reported by [2]. These points are excluded from the exponential fit (green) to the data. All data shown is binned in four hour periods. The normalized residuals are shown, calculated by

$$\Delta Rate = \frac{N_{obs} - N_{fit}}{N_{fit}}, \tag{5}$$

where N_{obs} and N_{fit} are the number of observed and expected counts, respectively. There is no clear deficit observed in correlation with the flare.

Figure 2 shows the relative deviation for the decay rate of ^{60}Co with respect to the fit measured by the UZH (a) and Nikhef (b) detector setups for timescales between 1 and 109 hours around the X9.3 flare, including the 1σ (blue) and 2σ (green) global confidence intervals. Note that, following equation (2), all points are correlated. We conclude, using the strength of our two independent setups, that all deviations are inside the bounds expected from statistical uncertainty. Within 1 hour around the Solar flare, the relative deviation observed in both setup is <0.4% and well within the global 2σ confidence interval. The UZH setup (a) observes an insignificant deficit is observed, while the Nikhef setup (b) observes an insignificant excess is observed. For both setups all points are within the global 2σ confidence interval.

In addition, all points of both ^{60}Co, the other measured isotopes (^{137}Cs and ^{44}Ti) and

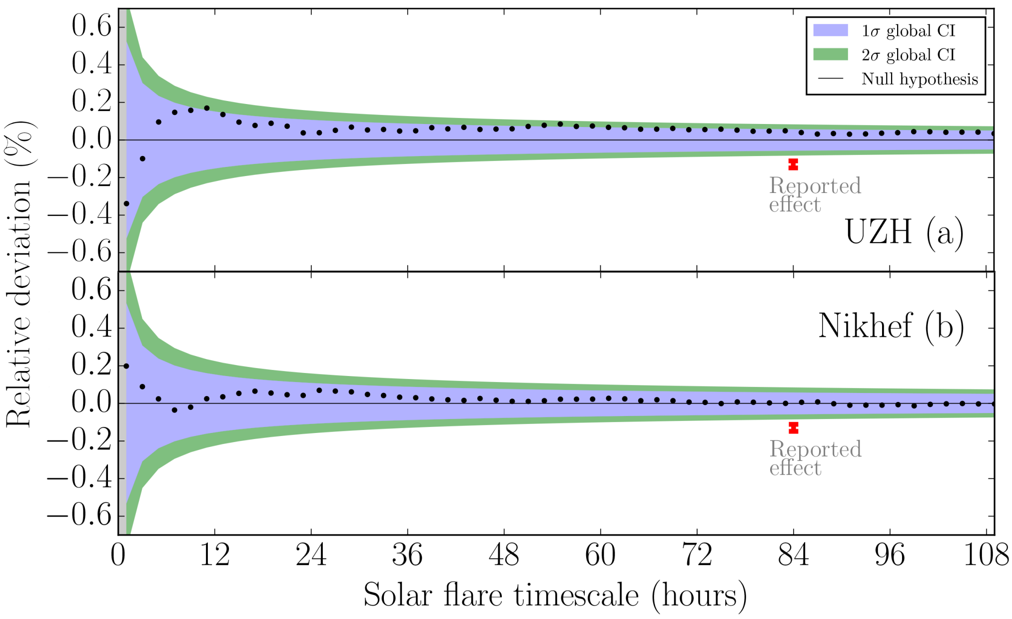

Figure 2: The result of the two-tailed test for the decay of ^{60}Co. The red data points in Figure 1 are used to calculate the relative deviation using equation (2) for the UZH (a) and Nikhef data (b). The black line corresponds to the null hypothesis which corresponds to normal exponential decay (equation 1). Every data point corresponds to a relative deviation with respect to the expectation, calculated by equation (2), over timescales around the Solar flare ranging from 1 to 109 hours. The global 1σ (blue) and 2σ (green) significance intervals are also included. The red data point denotes the reported effect by [2].

Table 1: Results of correlation of the decay rates of ^{60}Co, ^{137}Cs and ^{44}Ti and both Solar flares, measured by two different setups. In the one-tailed deficit test. The SW test, 2σ limit and the one-tailed test were all performed on a period of 84 hours.

Isotope	**Flare classification**	**Setup**	**2σ Lower Limit** (%)	**SW test** p-value	**One-tailed test** p-value
^{60}Co	X9.3	Zurich	-0.002	0.2	0.97
^{60}Co	X9.3	Nikhef	-0.043	0.5	0.54
^{137}Cs	X9.3	Nikhef	-0.033	0.08	0.40
^{44}Ti	X9.3	Nikhef	-0.009	0.005	0.86
^{60}Co	X8.2	Zurich	-0.036	0.5	0.71

of the correlation of ^{60}Co data measured at UZH with the second X8.2 Solar flare are well within the global 2σ confidence intervals. We therefore conclude that we observe no significant correlation between the decay rate and the Solar flares and all measured fluctuations are in this work paper consistent with bounds from statistical uncertainties.

From the continuously monitored slow control parameters we find that the variation (RMS) of the temperature, high voltage, magnetic field strength and radon activity are well within operating range as defined by Table 4 in [17]. We therefore conclude that systematic influences due to slow control parameters remain $<2 \cdot 10^{-5}$. The pressure and humidity were also monitored and remained stable during the full measurement period with 0.8% and 17% at the 68% CL, respectively.

Table 1 summarizes the correlated isotopes in this study. The lower limits and the p-values of the SW and one-tailed deficit test are presented for every monitored isotopes over a period of 84 hours. The SW test p-values (column 5) are >0.005. The lowest p-value of 0.005 is found due to one outlier within the tested period. The p-values from the one-tailed deficit test (column 6) are >0.4. From these p-values we conclude that for a period of 84 hours around the Solar flare, the distribution of the measured decay rate is consistent with a normal distribution and that we find no significant deficit with respect to the expectation.

Before we set a limit using the local test statistic (equation 3) and exclude the claimed hypothesis by [2], we correct for the imperfection of the performed fit over a finite number of data points. This imperfection causes a fluctuation in the fit parameters and influences the distribution of the local test statistic q. The weakest, most conservative exclusion and limit are found for the decay of ^{60}Co, measured by the setup at Nikhef (Figure 2 (b)) during the X9.3 flare. We exclude the hypothesis of [2] with 4.7σ confidence and set a lower limit on the deficit in decay rate to 0.044% with 2σ confidence. The lower limits of the other measured isotopes are listed in column four in Table 1. We conclude that our limits are not in agreement with the reported 7σ effect by [2].

4. Conclusion

We find no evidence for a correlation between Solar flare activity and a deficit or excess in the decay rate of three measured radioactive isotopes. A decrease in decay rate similar to the one observed by [2] is not found in either of our setups for ^{60}Co, ^{137}Cs and ^{44}Ti during two different Solar flares. We exclude the hypothesis claimed by [2] with 5.5σ confidence and set a lower limit with 2σ confidence on the deficit in decay rate for a period of 84 hours level at 0.044%, which is $\sim 2\times$ smaller than the reported effect of $\sim 0.1\%$. These results are consistent with findings of [6], who also do not observe a fractional effect larger than a few 0.01%.

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