Neutrino-Induced Decay: A Critical Review of the Arguments

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Abstract
There has been scientific debate about speculations that 'neutrino-induced' radioactive decay causes apparent violations of the exponential-decay law. Sturrock and others repeatedly publish papers asserting influences by solar and cosmic neutrinos on radioactive decay measurements and therefrom draw conclusions about space science that are highly speculative. Recurrent themes in their work are claims that the solar neutrino flux reveals oscillations at a monthly rate which can be linked to solar rotation, that annual and monthly oscillations occur in radioactive decay rates or directionality of emitted radiation which can be linked to variations in solar and cosmic neutrino flux hitting Earth's surface, and that unstable radioactivity measurements can be used as a source of information about the interior of the Sun and dark matter. Radionuclide metrologists have extensively investigated and refuted their arguments. Metrological evidence shows that radioactive decay does not violate the exponential-decay law and is not a probe for variations in solar neutrino flux. In this review paper, the main arguments of Sturrock are listed and counterarguments are presented. Reference is made to earlier published work in which the evidence has been scrutinised in detail.

1 Introduction

Recent nuclear science literature (McDuffie et al. 2020) abounds with claims from individuals who assert a correlation between variability in certain repeated radioactive decay rate measurements and rhythmic or abrupt changes in solar and cosmic neutrino flux hitting Earth (Falkenberg 2001; Jenkins and Fischbach 2009; Jenkins et al. 2009, 2012; Fischbach et al. 2009; Javorsek et al. 2010; Parkhomov 2018; Steinitz et al. 2011, 2018; Sturrock et al. 2012, 2013, 2016, 2018a,b, 2021a,b; Sturrock 2022). It is important to observe that many of these individuals are not specialised in radionuclide metrology, and that they often refer to experimental work performed by others. They seem to underestimate the difficulties associated with attaining stability in activity measurements and their analyses lack a proper

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metrological uncertainty assessment (Pommé 2015a, 2016). A prominent example of such work is the recent review paper by Sturrock (2022), which summarises arguments in favour of the concept of 'neutrino-induced decay' and draws unsubstantiated conclusions about solar dynamics.

Whereas science benefits from bringing forward new ideas, these ideas should be accompanied by sound arguments and strong evidence. In this case, the idea has lost momentum since the arguments have been convincingly refuted by evidence (Norman 2009; Krause et al. 2012; Bellotti et al. 2012, 2013, 2015a,b, 2018; de Meijer et al. 2011; Hardy et al. 2012; Kossert and Nähle 2014, 2015; Nähle and Kossert 2015; Pommé et al. 2016, 2017a,b,c,d, 2018a,b, 2019a,b, 2021, 2022; Angevaare et al. 2018; Pommé 2019; Pommé and De Hauwere 2020; Pommé and Pelczar 2020, 2022). At this matured stage of the research, there is a need for an overview paper that summarises the evidence in an objective manner, to avoid that invalidated arguments are being recycled to support unsubstantiated claims. In this paper, the main arguments put forward by Sturrock (2022) are scrutinised and the observed phenomena are discussed from a metrological point of view. For more detailed information, reference is made to the relevant literature in which the issues have been discussed in more detail.

One of the key statements made by Sturrock (2022) is that the solar neutrino flux impinging on Earth as measured in the Super-Kamiokande I (SKK-I) experiment in 1996-2001 (Yoo et al. 2003) shows a statistically significant cycle at a frequency of 9.43 a^{-1} (corresponding to a 38.7 days period), which allegedly bears witness of the dynamics of the solar interior. According to Sturrock et al. (2012, 2018a, 2021b), the same monthly frequency also shows up in a radon radioactivity experiment in Israel (Steinitz et al. 2011, 2018). Causality is hypothesised between solar neutrino flux and radioactive decay through the concept of 'neutrino-induced decay'. Consequently, radioactivity measurements on Earth should also undergo an annual cycle proportional to the seasonal variations of the solar neutrino flux along the elliptical track of the Earth around the Sun (Falkenberg 2001; Jenkins et al. 2009; Fischbach et al. 2009). Recently, Sturrock (2022), Sturrock et al. (2021a) gave up the idea that the neutrino *induces* beta decay – 'a red herring', Sturrock admits – and instead they assert that the neutrino *redirects* the spontaneous decay in a way that the radiation from the decayed nucleus is preferentially emitted in the direction of the flightpath of the neutrino.

Extensive measurement campaigns of decaying sources over several years in various metrological laboratories on four continents show that there is no common annual cyclic effect in phase with Earth-Sun distance (Pommé et al. 2016, 2017a,b,c). Accurate activity measurements performed in stable conditions show no monthly cycles, disproving the claimed association with internal solar dynamics (Pommé et al. 2018a; Pommé and De Hauwere 2020). The instability in certain radioactive decay measurements could be linked to radon emanation (Siegert et al. 1998, Schrader 2010, 2016, Pommé et al. 2017a), temperature inside the laboratory (Pommé et al. 2017a), temperature and humidity in the environment (Pommé et al. 2021, 2022; Pommé and Pelczar 2020, 2022), as well as solar irradiance and rainfall (Pommé et al. 2018b; Pommé 2019). From a theoretical point of view, the interaction probability of a neutrino with a nucleus is too low to induce (inverse) beta decay rate changes in the permille (0.1%) range.

The disputed assertions that will be addressed in this review are:

– the significance of monthly oscillations in solar neutrino flux measurements (Homestake, Gallex, GNO, Super Kamiokande I, Borexino)
– the annual oscillation in tritium activity measurements by Falkenberg
– the annual cycle in ^{32}Si decay measurements at the Brookhaven National Laboratory (BNL) and ^{36}Cl at the Ohio State University Research Reactor (OSURR)

– the annual cycle in ^{90}Sr/^{90}Y and ^{60}Co decay measurements at the Russian Academy of Natural Sciences
– the daily, monthly and annual oscillations in radon measurements at the Geological Survey of Israel (GSI)
– the interpretation of the radon experiments by Bellotti et al. at the Gran Sasso National Laboratory (LNGS)
– the conjecture that radiation emitted in the deexcitation process following neutrino-influenced decay is directionally aligned with the trajectory of the neutrino.

2 Monthly Cycle in Solar Neutrino Flux

2.1 Homestake, Gallex and GNO

Sturrock (2022) depicted the history of early experiments designed to measure the solar neutrino flux and the puzzling anomalies in the obtained results. According to Sturrock, analyses of the Homestake, Gallex-GNO and Super-Kamiokande I measurements reveal evidence of variability of the solar neutrino flux. Characteristic frequencies in power spectra were commonly sought in the 10-15 a^{-1} frequency range, which is of interest for hypothetical associations with internal solar rotation. Weak resonances were indicated in the Homestake data at e.g. 12.88 a^{-1} and 13.85 a^{-1}. These peaks did not occur in the combined Gallex-GNO power spectrum, where the main peak was found at 13.59 a^{-1}. None of these frequencies is predominantly present in the SKK-I data, in which peaks at 9.43 a^{-1} and 12.31 a^{-1} are the most prominent ones. Even though these three power spectra show no resemblance in their characteristic frequencies, Sturrock interprets the main resonances as being statistically significant and indicative of oscillations in the solar interior. He made free associations with modulations of the neutrino flux in the radiative zone (situated deep inside the Sun) and inferred that the axis of rotation doesn't coincide with the normal of the ecliptic (creating an "oblique rotor effect"). However, Sturrock did not address the obvious mutual inconsistency of the resonances in the power spectra of these experiments.

One can question the statistical significance of the peaks in the Homestake and Gallex-GNO power spectra, since the highest peaks in the periodograms presented by Sturrock (2022) have a power below 6. A periodogram of the Gallex data in the 6-16 a^{-1} range is shown in Fig. 1. Resonances of such magnitude appear also in analyses of normally-distributed random noise. The corresponding chance that the power of a fitted sinusoidal cycle at a particular frequency exceeds a value S is calculated from an exponential function
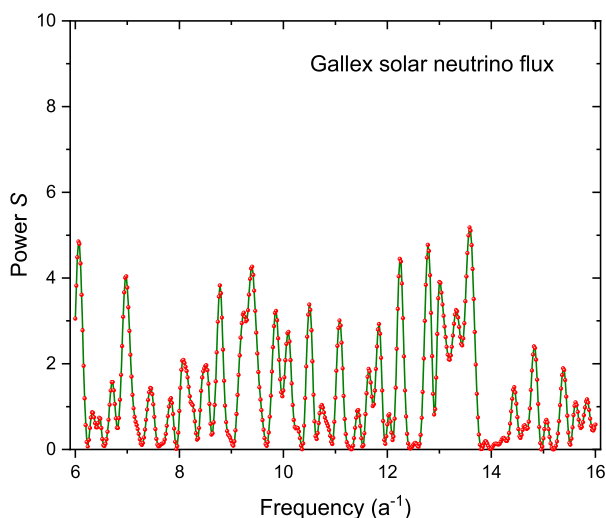
$$P_1 = e^{-S} \qquad (1)$$

When performing a scan of the data set at N independent frequencies, the probability that at least one peak above power S is found is calculated from

$$P_N = 1 - (1 - P_1)^N \qquad (2)$$

In power spectra of sinusoidal cycles fitted to Gaussian-distributed noise, only $P_1 = 0.25\%$ of the power values is larger than 6, but the probability P_N of finding at least one such peak when scanning e.g. $N = 300$ frequencies exceeds 50%. Hence, there is no statistical argument to claim that Homestake and Gallex-GNO neutrino flux data show irrefutable evidence for the existence of sinusoidal patterns.
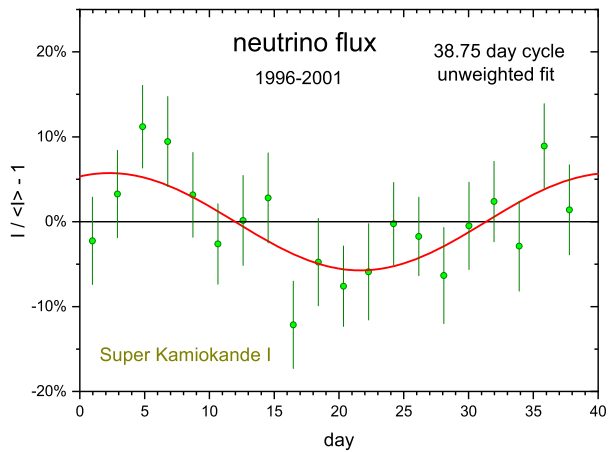
2.2 Super Kamiokande I

The Super-Kamiokande is a gigantic imaging water Cherenkov detector able to detect neutrinos with energies between a few MeV and a few hundred GeV (Suzuki 2019). A search for periodic modulations of the solar neutrino flux was performed using the SKK-I data taken from May 31st, 1996 to July 15th, 2001 (Yoo et al. 2003). Arguably, the resonance at 9.43 a^{-1} is at the edge of statistical relevance. There has been debate on this issue with subtle differences in the data analysis and opposing conclusions, either that the high power value is just a random peculiarity of the data set (Yoo et al. 2003; Ranucci 2006; Desai and Liu 2016, Pommé et al. 2017d, 2018a) or on the other hand a meaningful feature of physical origin (Sturrock et al. 2013, 2016, Sturrock 2022).

Analysis of the 5-day averaged neutrino flux data set has shown that the χ^2 reduces by not more than 0.054% when a sinusoidal function is matched to the data (Pommé et al. 2017d). If there is a cyclic effect, it is minute in comparison with the experimental uncertainty. Pommé and De Hauwere (2020) presented a simple relationship between the amplitude of the fitted cycle, the uncertainty of the measurement data and the power of the cycle. Pommé (2020) has derived the relevant statistical equations for four variations of the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982; VanderPlas 2018), either using statistical weighting or not and either co-fitting a free baseline value C together with the sine function or not.

When performing an analysis without statistical weighting, the measurement uncertainty can be estimated from the relative standard deviation of the data set σ_y. Assuming that the set of n measurements data is somewhat randomly distributed in time over one or more full periods, the phase variable $x = \sin(\omega t + \varphi)$ follows an Arcsine distribution and the amplitudes A of fitted sinusoidal functions is Rayleigh distributed (Pommé 2020). In principle, the latter is only true if the amplitude A is first normalised by a factor $\sqrt{2s_x^2}$ – with s_x, the standard deviation of x – although for the SKK-I data set this factor approaches unity (Pommé 2020). The power S relates to the ratio of the normalised amplitude to its standard uncertainty

$$k = A/\sigma_A \tag{3}$$

Fig. 2 Unweighted fit of a sinusoidal function with a frequency of 9.43 a^{-1} to the SKK-I data set. The data in the graph have been binned into 20 equal time intervals to ease a visual comparison with the fit to the original data set

through

$$S = k^2/2 \tag{4}$$

and, with $C = \langle y \rangle$ as a free parameter, the expectation value for σ_A is (Pommé 2020)
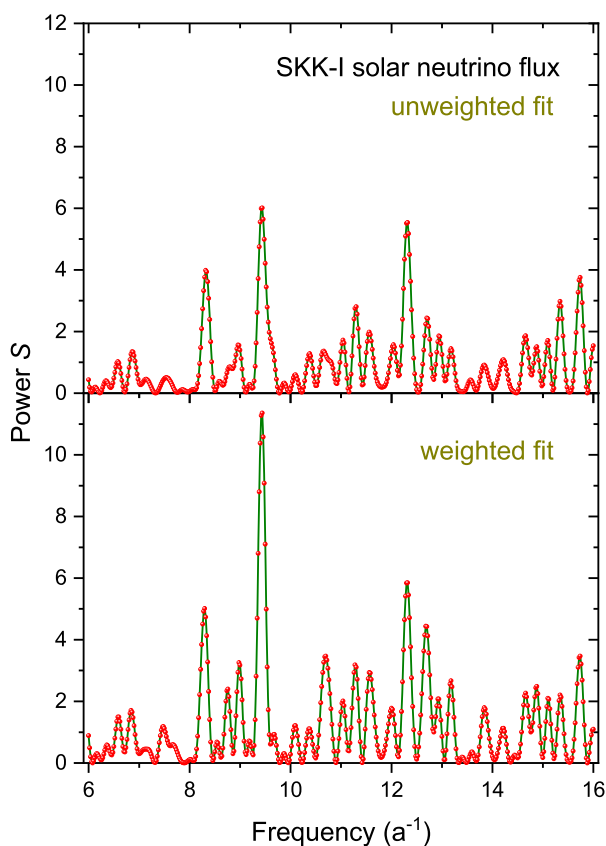
$$\sigma_A^2 = \frac{2}{n-1} \sigma_y^2 \tag{5}$$

The SKK-I data set consists of $n = 358$ measurement results with an average value of $\langle y \rangle = 2.35$ and a standard deviation $\sigma_y = 0.50$, which results in a relative uncertainty of $\sigma_y/\langle y \rangle = 21.3\%$ and $\sigma_A/A = 21.3\% \sqrt{2/357} = 1.60\%$. The fitted amplitude for the resonance at 9.43 a^{-1} is $A = 5.73\%$ (Fig. 2) and therefore $k = 3.6$, $S = 6.5$ and $P_1 = 0.15\%$. When scanning >500 independent frequencies, the probability of finding at least one such power value is $>50\%$. This is consistent with the *a priori* assumption that there is no significant modulation.

When performing a weighted fit, the quality of the uncertainty estimate assigned to each individual measurement value is crucial for the interpretation of the statistical significance of the resonances. The reported uncertainty values are asymmetric and vary mildly (by about 20%) among data points. For the sake of simplicity of the current exercise, a symmetric uncertainty value has been assigned to the data calculated as the mean value of σ_- and σ_+. On average, one finds an estimated relative uncertainty of 20.6% on the measurement data, which does not completely cover the observed standard deviation of 21.3%. This can either point to some underestimation of the error or to the presence of non-random structure in the data. Since data with low uncertainty have a higher impact on the weighted fit, the effective number of data points is calculated from (Pommé 2020)

$$n_{\text{eff}} = \left(\Sigma w_i^2 \right)^{-1} \tag{6}$$

in which the normalised weight w_i is proportional to the inverse of the variance ($w_i = \sigma_i^{-2}/\Sigma \sigma_k^{-2}$) and the sum of all weights equals 1 ($\Sigma w_i = 1$). This results in $n_{\text{eff}} = 321$, which is not much lower than $n = 358$ due to the rather mild differences in statistical weight among the data points. The corresponding uncertainty of the amplitude is estimated from

Fig. 3 Unweighted (top) and variance-weighted (bottom) periodogram (with free baseline constant) of the Super Kamiokande I solar neutrino flux data set. Only in the weighted version is the modulation at 9.43 a^{-1} close to statistical significance
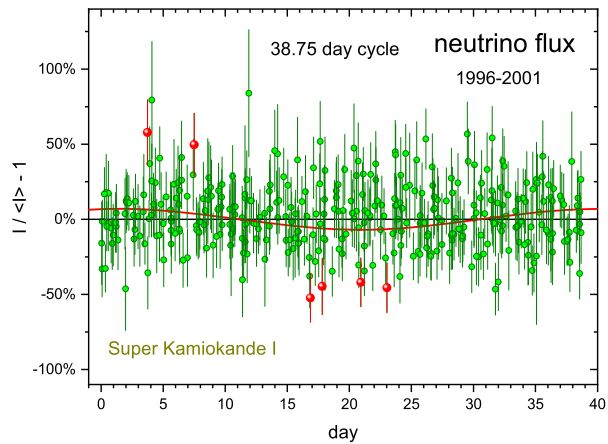
the uncertainty on the weighted mean of the residuals

$$\sigma_A^2 = \frac{n_{\text{eff}}}{n_{\text{eff}} - 1} \frac{\sigma_{y_w}^2}{s_x^2} \approx 2\sigma_{y_w}^2 \qquad (7)$$

in which $\sigma_{y_w}^2 = \left(\Sigma\sigma_i^{-2}\right)^{-1}$. It is crucial to understand that underestimation of measurement uncertainties σ_i will unavoidably lead to underestimation of $2\sigma_{y_w}^2$ and σ_A in Eq. (7), hence overestimation of k in Eq. (3) and the power S in Eq. (4), thus underestimation of the probability values in Eqs. (1) and (2), which eventually may lead to false indications of statistical significance of certain resonances. The effect of statistical weighting to the SKK-I data is demonstrated in Fig. 3, which compares the weighted and unweighted periodograms.

The variance-weighted fit of the SKK-I data results in an amplitude of 6.90% with uncertainty 1.45%, which indeed leads to an unusually high power of 11.4 at quite low odds of $P_1 = 0.001\%$ and $P_{500} = 0.58\%$. This outcome is influenced disproportionally by not more than 10 extreme data with $\chi^2 > 5.5$. When these data are excluded from the weighted fit, thus keeping 348 data with $\chi^2 < 5.5$, the fitted amplitude drops to 5.58% and $P_{500} = 25\%$. In fact, it is a subset of 6 data only that pull the amplitude to an unusually high value. The mere exclusion of those 6 values, leads to a much lower amplitude of 5.3%. It seems that the uniqueness of this resonance rests on the fortuitous alignment of 6 extreme data out of a set of 358 (Fig. 4). This is a weak basis for inference of new physics.

Fig. 4 The SKK-I data set with symmetrised uncertainty values as a function of time *modulo* a period of 38.75 days. The six data in red pull the weighted fit of a sinusoidal function (line) towards an unusually high amplitude

2.3 Borexino

Borexino measures solar neutrinos via their interactions with a target of 278 ton organic liquid scintillator located underground in the LNGS at Gran Sasso, Italy. They are detected after elastic neutrino-electron scattering through photons generated by the kinetic energy of the electrons. In 2017, the Borexino collaboration (Agostini et al. 2017) published an analysis of 4 years of measurement in the Phase-II period December 2011-December 2015. The annual flux modulation could be revealed easily, e.g. through mode decomposition analyses (Agostini et al. 2017; Pommé and Pelczar 2021), and was found to be compatible in amplitude and phase with that expected from the eccentric revolution of the Earth around the Sun. An unweighted periodogram of the data shows no peaks with a power above 4.6 in the frequency range 2 a^{-1}-18 a^{-1} (Agostini et al. 2017), which bears witness of a remarkable stability of the neutrino flux. A variance-weighted periodogram is shown in Fig. 5. The total absence of signatory resonances in the Borexino neutrino flux data was not reported by Sturrock (2022), yet seems to undermine the basis of his inference regarding the internal solar dynamics.
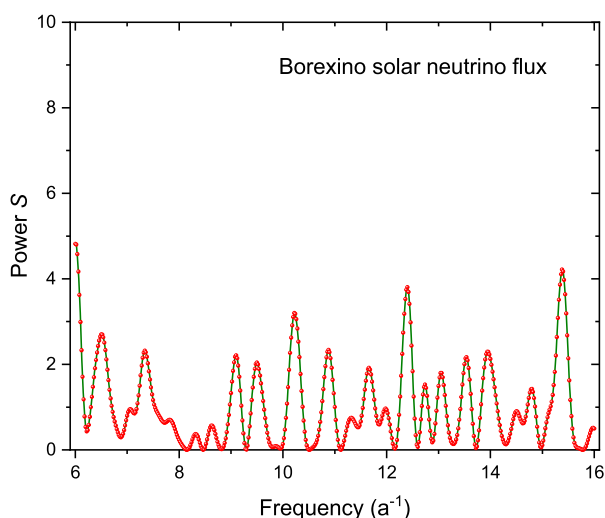
2.4 Intermediate Conclusion

Other than the obvious annual cycle, there are no statistically significant resonances in the solar neutrino flux measurements derived from the Homestake, Gallex, GNO, Super-Kamiokande I, and Borexino experiments. There is no communality of frequencies with relatively higher power values among these data sets. Association of such peaks with internal solar rotation is purely speculative and can be discarded on statistical grounds.

3 Annual Cycle in Beta Decay Measurements

3.1 The Falkenberg Experiment

Falkenberg (2001) reported the results of an experiment aimed at testing the hypothesis that radioactive beta decay might be caused by the neutrino flux coming from the Sun and other sources. The author was inspired by Nicola Tesla who speculated that radioactivity might

Fig. 5 Periodogram –
variance-weighted with free
baseline (Pommé 2020) – of the
solar neutrino flux measured with
the Borexino detector at the
LNGS underground laboratory.
There are no statistically
significant modulations in the
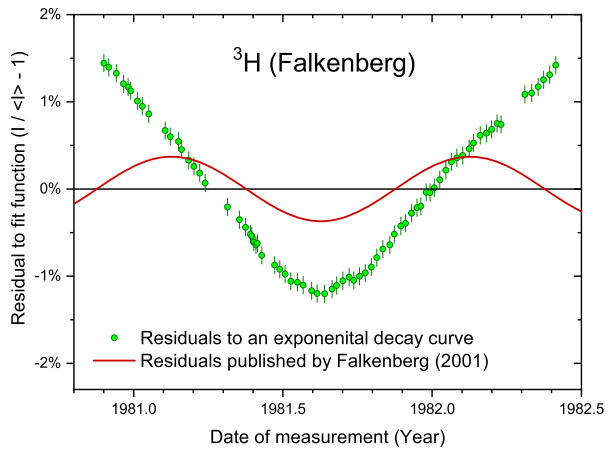monthly frequency range

be caused by small particles that are omnipresent and capable of passing (non-radioactive) matter almost without leaving any trace. Falkenberg incorporated tritium atoms inside a strip of phosphorescent material and placed it in front of an array of photodiodes. He repeated decay rate measurements over a period of 2 years and fitted a double exponential function to the data. The residuals to the fitted 'decay curve' showed a sinusoidal deviation hinting to an annual cycle with 0.37% amplitude in the beta decay of tritium. Sturrock (2022), Sturrock et al. (2016, 2018a, 2021a,b) and others (Fischbach et al. 2009, 2018; Milián-Sánchez et al. 2020) repeatedly refer to this paper to imply that solar neutrinos induce violations of the exponential-decay law of beta emitters.

However, Falkenberg's experiment was so badly conceived that the tritium disappearance rate was seemingly much higher than expected from beta decay alone, yielding a fitted 'half-life' value of 2.26 a instead of the true value of $T_{1/2}(^3\text{H}) = 12.312$ (25) a (Chechev 2006). One may assume that a major fraction of the tritium disappeared from the source due to its volatility. Moreover, Falkenberg has artificially introduced the apparent 'annual modulation' into the data analysis by adding an arbitrary fit function to represent the 'degradation of the experiment'. It can be easily demonstrated that the residuals to an exponential decay function without this superfluous 'correction' show no annual oscillation, but rather a V-shape indicative of a drastic change of the disappearance rate halfway the experiment (Fig. 6). This artefact has been exposed by Bruhn (2002) and Pommé et al. (2017b), yet up to the present date Sturrock and others have failed to recognise the invalidity of the Falkenberg experiment as an argument in favour of neutrino-induced beta decay. Accurate measurements of tritium decay with a liquid scintillation counter at the JRC demonstrate that there is no annual violation to the exponential-decay law within 0.022% standard uncertainty on the amplitude (Pommé et al. 2017b).

3.2 The BNL and OSSURR Experiments

A typical argument raised to advocate the idea of 'neutrino-induced beta decay' (Jenkins et al. 2012, Sturrock et al. 2016, 2021a, Sturrock 2022) are the annual oscillations at permille level observed in decay rate measurements of the beta emitter ^{32}Si by Alburger et al. (1986) at the BNL in Upton (NY), USA and ^{36}Cl by others at the OSURR in Columbus (OH),

Fig. 6 Residuals of the ^{3}H decay rates measured by Falkenberg (2001) to a purely exponential decay function (dots) and the sinusoidal shape (line) claimed by Falkenberg on the basis of an arbitrary decay function

USA. The latter measurement series was described by Jenkins et al. (2012). The reader is referred to Fischbach et al. (2018) for a picture and description of the BNL detector set-up (and to Breur et al. (2020) for a rebuttal to their claim that gravitational waves were observed through radioactive decay).

The beta particles emitted by the source travel a short distance in air, pass a window material to be finally detected in a gas detector. Since the beta particles have a continuous energy distribution, a fraction of them is too low in energy to pass through these materials and deliver a signal that surpasses the electronic threshold. From a metrological point of view, it is obvious to suspect that energy loss in air as well as electronic amplification can be influenced by environmental conditions. However, this is denied by Jenkins et al. (2012) who speak of 'a robust detector system with very low susceptibility to environmental changes' and Sturrock (2022), Sturrock et al. (2016, 2021a) who misquote Alburger et al. (1986) to suggest that the observed variations in the decay rates are 'of uncertain origin'.

Alburger et al. (1986) followed the decay curve of ^{32}Si to determine its half-life. This was a rather carefully executed experiment, however the authors realised with time that their detection efficiency was susceptible to influences from ambient temperature and air humidity. Only at later stages of the campaign did they keep track of environmental parameters, so they were unable to correct the results for apparent correlations with weather conditions. They literally stated that 'of all the parameters either tested or considered, temperature and relative humidity seem to be the only ones that could affect the ^{32}Si/^{36}Cl ratio at the level of one standard deviation.' It is clear from several considerations in their paper that the authors were well aware of the most probable origin of the annual cycle in their measurement results. Pommé et al. (2021) used historical meteorological data from a nearby weather station to confirm that there is a striking correlation ($R^2 = 0.38$) between the variations of the ^{32}Si decay rates measured at BNL with the local ambient temperature and dew point at that time, whereas they are out of phase with the annual neutrino flux changes ($R^2 = 0.24$). Correlation plots are shown in Fig. 7.

The evidence is even more compelling for the ^{36}Cl decay rates measured at OSURR (Pommé et al. 2021). The coefficient of correlation between residuals (raised to the power -2.5) over periods of 2-3 years with matching dew point data is $R^2 = 0.80$ (Fig. 7). This is convincing proof that this type of measurements of beta particles is highly susceptible to outside weather conditions, since ambient humidity can also enter a temperature-controlled
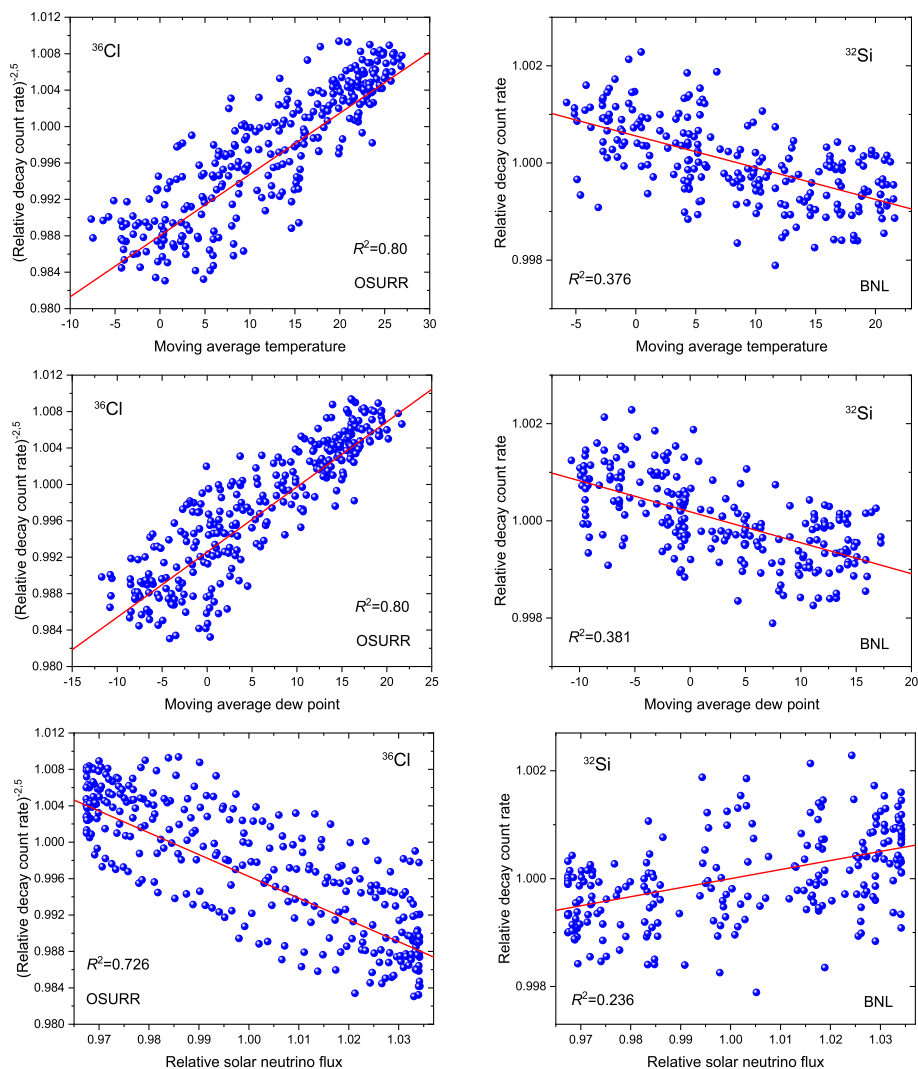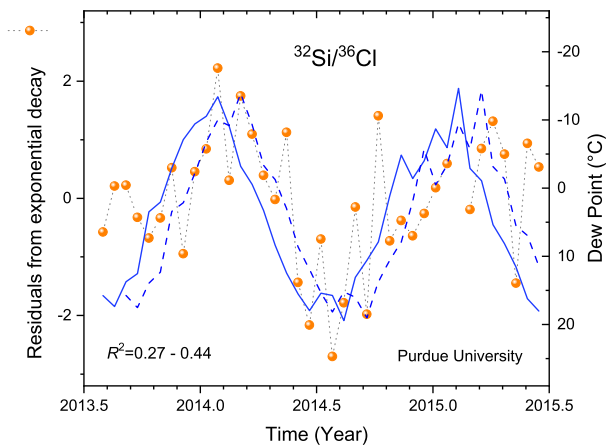
Fig. 7 Correlation plots of residuals to exponential decay of ^{36}Cl (Jenkins et al. 2012) and ^{32}Si (Alburger et al. 1986) with ambient temperature, humidity and solar neutrino flux

laboratory. Citation of this work and mentioning of these important conclusions are lacking in the review paper of Sturrock (2022).

Sturrock has searched for characteristic frequencies in the ^{32}Si decay rate data of BNL and found the most statistically significant periods at 1 a^{-1} ($S = 24$) and 11.17 a^{-1} ($S = 21$). Interestingly, the latter frequency has not been observed in the discussed solar neutrino flux data, but that does not discourage Sturrock (2022) from concluding that 'this raises the possibility that this observation may have its origin in internal solar processes, the interior rotating more slowly than the visible surface'. Obviously, it would make more sense to conclude that the frequency analysis bears witness of changing weather conditions on Earth.

Fig. 8 Residuals (dots) of ^{32}Si/^{36}Cl decay rates from an exponential curve (Heim 2015) versus the ambient dew point in Purdue (line), averaged over periods of 18 days. The correlation coefficient is $R^2 = 0.27$ and goes up to $R^2 = 0.44$ when a time delay of 0.1 a is applied (dashed line)

The instability at a monthly scale may reflect the occurrence of changes in humidity as weather systems evolved.
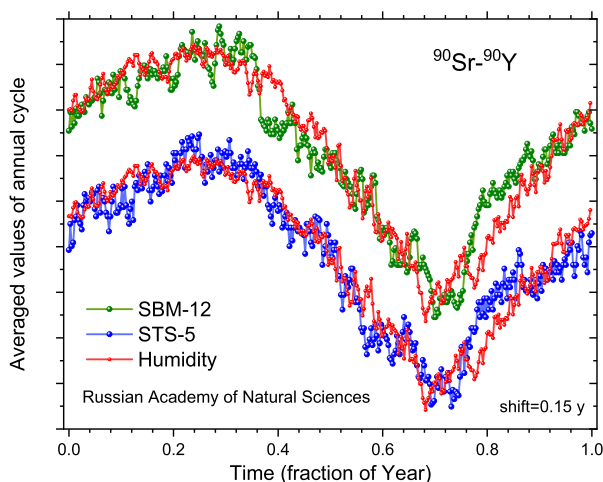
The BNL set-up was later moved to Purdue University and the experiment was continued in 2013-2015 (Heim 2015). Seasonal instabilities appeared again in the measured decay rates, roughly in phase with the NBL data. It was found that variations in the detector voltage have a disparate effect on the measured decay rates of the ^{32}Si source and the ^{36}Cl check source. An increase in voltage brings fractionally more low-energy counts into the integration region for ^{36}Cl than what is pushed out at the upper end, whereas the opposite is true for ^{32}Si (Heim 2015). It seems that ^{32}Si is mostly detected indirectly through the highly energetic beta decays from its progeny ^{32}P (Pommé et al. 2021). Anyway, the stability of the experiment is affected by a variable cut-off in the beta spectra at the low end as well as at the high end, which may cause some phase shift with respect to the driving mechanism(s) behind gain changes. In spite of the low statistical accuracy of the decay rate measurements, their residuals from exponential decay (Fig. 4.32 in Heim 2015) appear anti-correlated with the dew point observed in the local weather station (Weather Underground 2022), as shown in Fig. 8.

3.3 The Parkhomov Data

Somewhat similar to the BNL/Purdue and OSSURR experiments, Parkhomov (2018) at the Russian Academy of Natural Sciences in Moscow (Russia) followed the decay rate of external ^{90}Sr/^{90}Y and ^{60}Co beta sources with Geiger–Müller counters over periods of several years. The residuals of the ^{90}Sr/^{90}Y data to a purely exponential decay curve in two counters show an obvious annual cycle which resembles the inverse shape of the absolute humidity in air in Moscow (Pommé et al. 2022), albeit with a phase shift of about 0.05-0.15 a (Fig. 9). Since the influence of environmental parameters could not be disentangled unambiguously in retrospect, it is clear that these experiments suffer from a lack of uncertainty evaluation regarding their stability towards various potential influencers, in particular ambient humidity.

The decay rates are not in phase with the annual variation of the solar neutrino flux on Earth, since the maxima are situated in the spring instead of early January (Fig. 9). Parkhomov came up with an alternative explanation that beta decays may be influenced by 'cosmic slow neutrinos'. Sturrock (2022) explored this possibility. Since the effect of the

Fig. 9 Averaged decay-corrected count rates of ^{90}Sr/^{90}Y beta decay obtained by Parkhomov (2018) with the SBM-12 (top) and STS-5 G–M counter (bottom) as a function of time in the year, compared to absolute humidity in Moscow calculated from weather data shifted in time by 0.15 year to the right (line)
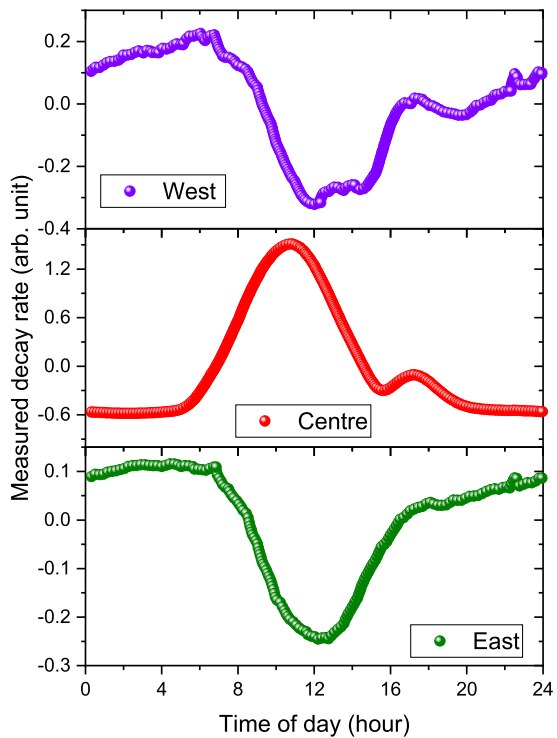

solar neutrinos would be overshadowed by the cosmic neutrinos, the cosmic flux would have to be comparably large and this would have implications on the density of the dark matter and the neutrino mass. These are interesting speculations, but the plot twist is even more impressive: suddenly the influence of solar neutrinos on beta decay is deemed negligibly small and the emphasis is moved to a 'focussed beam' of slow neutrinos coming from cosmic dark matter. It raises many questions, not only about the lack of empirical evidence for such cosmic slow-neutrino flux. Why has this seasonal effect not been observed in other beta decay measurements? Why are the BNL/Purdue and OSSURR data not in phase with Parkhomov's data? Are those beta decay experiments no longer a magnifying glass for solar neutrinos? Should the monthly frequencies from now on be ascribed to processes regarding cosmic dark matter instead of solar rotation?

It suffices to mention that radionuclide metrology laboratories, which use robust activity measurement techniques like triple-to-double coincidence rate counting (TDCR) (Kossert et al. 2015) or ionisation chamber measurements (Schrader 2007; Pommé et al. 2018c), confirm that there are no annual oscillations in the decay of ^{90}Sr/^{90}Y and ^{60}Co or other beta emitters at an accuracy level in the order of 0.007% (Kossert and Nähle 2015, Pommé et al. 2016, 2017b). It appears that only unstable activity measurements qualify for feeding speculations concerning space science.

3.4 Intermediate Conclusion

It is obvious that detections of beta particles from an external source by means of G-M counters is susceptible to weather conditions. This type of set-up is unsuited for stable activity measurements and therefore not used by radionuclide metrologists at standardisation laboratories. Frequency analyses may indeed reveal statistically significant perturbations, but the interpretation should reflect on the conditions that truly influence the outcome of the experiment. Temperature and humidity are important influencers, and their contribution should be ruled out completely before hypotheses of exotic processes can be tested. The hypotheses that beta decay is influenced either by solar neutrinos or cosmic neutrinos are mutually conflicting regarding timing and interpretation.

Fig. 10 Average daily variations in the measured decay rates from radon decay series measured in the West, Central and East gamma detector by Steinitz et al. (2018)
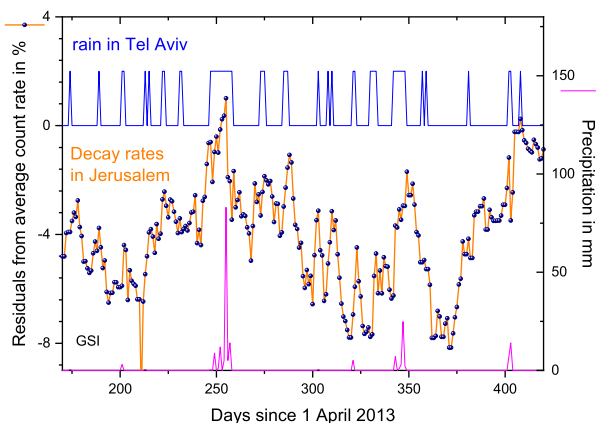

4 Cycles in Radon Measurements

4.1 The GSI Experiment

The critique on the review paper of Sturrock (2022) culminates in the interpretation of the GSI radon experiment by Steinitz et al. (2011, 2018), which consists of extensively repeated measurements of decay rates of radon gas traveling freely inside a closed canister in the garden of the GSI in Jerusalem, Israel. The set-up is partially protected by a makeshift covering hut that is open at the south side, and therefore still exposed to sunlight, rainfall and wind. A gamma detector with lead shielding and two alpha detectors are suspended in the sealed tank containing phosphorite rock which emanates radon (^{222}Rn and short-lived ^{220}Rn) and its progeny. Two additional external gamma detectors are fixed to the hut at the east and west side, at the height of the air volume in the tank. The decay rates show a plethora of daily and seasonal instabilities, which differ from one detector to another. For example, in Fig. 10 the average daily variations in the west, central, and east gamma detectors are shown.

Pommé (2019), Pommé et al. (2018b, 2019b) have explained in detail how these in-stabilities are highly correlated with local weather phenomena. In this paper, only a short summary is given of their findings. The marked peak in the central detector is proportional to the power generated by solar irradiance in Israel. The timing and amplitude of this peak at noon, both on a daily as on a seasonal level, can be predicted on the basis of a solar power model. A local dip occurring 1-2 hours before the end of daylight (in every season) may hint to the effect of a recurrent local shadow cast by a nearby object. The noon peak sometimes

Fig. 11 Daily minimum count rates (dots) (occurring at night) measured with the Gamma-C counter at the GSI in Jerusalem, compared to an indication of the days with rainfall and the amount of precipitation measured at the airport in Tel Aviv. The baseline rises systematically in rainy periods and decreases afterwards
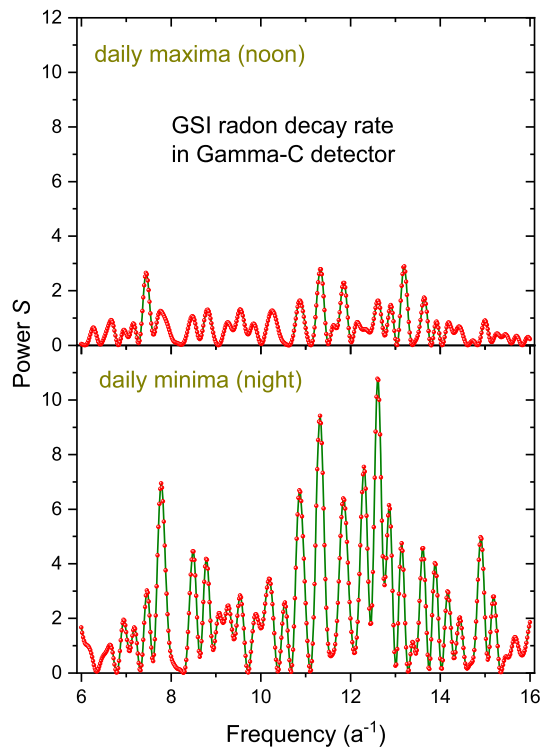

disappears on cloud-covered, stormy days and may return with high amplitude the next day. The lateral gamma detectors experience a major dip at noon, roughly in antiphase with the central detector. The bottom alpha detector seems to reflect the temperature dependence of the radon emanation rate of the ore, and the top alpha detector shows a local dip one hour before sunset and extraordinarily large peaks at extremely hot days. At night, the detectors return to a steadier baseline value, which varies slowly with seasonal changes in ambient temperature and jumps up abruptly with rainfall, in particular in stormy conditions with southern wind. After rainy periods, the baseline level returns to 'normal' in a few days.

The air and radon gas in the tank mix through diffusion and convection. The radon progeny, initially electrically charged, attaches to aerosol particles or deposits on surfaces. Temperature gradients in the tank build up when the solar irradiance heats up the side wall of the canister. The radon will preferentially migrate to colder spots, such as the bulky central detector and its shielding, which have a more stable temperature owing to their high heat capacity. The radon being more concentrated in the central part, results in an increased decay rate in the central detector and a dip in the lateral detectors, as observed in Fig. 10. In summer, the daily pattern is quite regular, whereas in winter extreme aberrations are observed in the peak height and the baseline of the data. This is clearly associated with rainfall and cloud cover, which is common in winter and rare in summer, and the ensuing humidity visibly disturbs the detector response for several days. The susceptibility of the nocturnal base count rate to rainfall is demonstrated in Fig. 11.

In spite of the overwhelming evidence, Sturrock (2022) insists that 'there is no correlation between the gamma measurements and the environmental measurements'. He argues that any environmental effect is 'obviously ruled out' because the power of the annual cycle in the noon peak 'corresponds to a false-alarm probability of less than 10^{-1700}' (Sturrock et al. 2021a), as if the power of a cycle has any bearing on its provenance. This is a questionable argument, at variance with the observations. Moreover, it makes little sense to perform a power analysis on data sets contaminated with environmental effects. For what it is worth, Sturrock et al. (2021a) identified some 'solar rotation' frequency pairs, however these frequencies do not appear consistently among the three detectors inside the canister (Pommé et al. 2018b). For reference, an unweighted periodogram of maximum and minimum count rates in the central gamma detector is shown in Fig. 12.

As for the interpretation of the data, Sturrock has abandoned the original idea that solar neutrinos increase the beta decay rate and now claims that neutrino-influenced decay aligns the subsequently emitted radiation with the direction of the neutrino. Since ^{222}Rn and most

Fig. 12 Periodogram of daily maximum and minimum values of the decay rates measured in the central gamma-ray detector at GSI in 2007-2011 Pommé et al. (2018b). The nocturnal data are susceptible to time differences between rain showers

of its decay products are alpha emitters, it is assumed that these nuclides are not affected by interaction with the neutrino. The most plausible candidates responsible for the hypothetical solar-induced cycles in the decay series of ^{222}Rn would be the beta emitters ^{214}Pb and ^{214}Bi, since their decay is followed by significant gamma-ray emission. They are short-lived (27 min and 20 min) such that decay formulas (Pommé et al. 1996) show that they are in secular equilibrium with their parent nuclides and that subtle changes in their decay constants cannot explain monthly cycles in the activity (Pommé et al. 2018b). On the other hand, under the 'directionality' hypothesis an increase in detection rate of deexcitation gamma rays can be expected when the neutrinos fly in a direction from the radioactive source towards the detector.

Since the sensitive part of the central gamma detector is facing down, the positive peak at noon cannot be caused by solar neutrinos, because they would direct the gamma rays away from the detector. Therefore, Sturrock asserts that the decay rate variations during daytime are generated by cosmic neutrinos, whereas the nocturnal data are influenced by the solar neutrinos. He gives no explanation why the peaks at noon are large in summer and small in winter and is apparently not alarmed by the fact that the diurnal effect caused by the 'cosmic neutrinos' is synchronised with and proportional to the solar irradiance in Israel. Sturrock has also not given an explanation for the fact that the east and west detectors do not reveal a positive peak as the Earth turns around its axis, only a negative dip at noon.

The nocturnal radon decay rate data of the central detector are interpreted as indicative of 'solar rotations', whereas the obvious correlations with temperature, rainfall and cloud cover are disregarded and the different temporal behaviour in the other four detectors is ignored. Merely on the basis of a periodogram of unstable radon decay measurements (cf.

bottom graph in Fig. 12), Sturrock (2022) draws conclusions about 'influence of the solar internal magnetic field by the resonant spin-flavor precession process', 'pairs of oscillations separated by 1 year', 'misalignment of internal rotation axes with respect to the normal to the ecliptic', 'a triplet of oscillations attributed to the core and a rotation axis approximately orthogonal to that of the solar photosphere', 'the Sun having its origin in more than one stage of condensation', and 'layers of the solar interior that have different metallicities, as well as different rotation rates and axes'. Whereas comments on the veracity of these conjectures are not in the scope of this paper, it has to be emphasised that they are neither corroborated nor contradicted by the radon measurement studies.

4.2 The LNGS Experiments

Bellotti et al. (2015b) at the LNGS in Gran Sasso, Italy have demonstrated that a tiny temperature gradient of 0.01 °C inside an air-filled glass sphere suffices for radon to occupy preferentially the colder places in the gas volume. Such effect is used to the extreme in a primary standardisation technique (Pommé 2007, 2022a,b) based on the counting of alpha particles at a defined solid angle (Pommé 2015b), by condensation (Ferreira and Lobo 2007) of gaseous radon on a cold finger (Picolo 1996; Spring et al. 2006). The large fluctuations in the apparent radon decay rate measured outside the glass sphere could be removed by impeding the free displacement of the radioactive nuclei inside the gas volume, e.g. by filling the volume with spherical polystyrene particles (0.7-0.9 mm diameter) or by diffusing the radon into olive oil.

Sturrock (2022) ignores the well-established fact of mobility of radon gas in air and claims that the 'directionality' of neutrino-aligned decay is stronger in air than in other 'opaque' media. Counterevidence against the idea of directionality of radiation emission will be discussed in the next section of the paper.

4.3 Intermediate Conclusion

There is not a shred of evidence of a correlation between decay rate measurements of radon series and the solar or cosmic neutrino flux. In reality, the radon experiments by Bellotti et al. (2015b) and Steinitz et al. (2018) show the effects of free mobility of the radon gas along temperature gradients inside a closed canister. Temporal changes in the outcome of the GSI experiment are largely caused by solar irradiance and rainfall.

5 Neutrino-Beta-Gamma Directional Correlation

5.1 The Directionality Hypothesis

Sturrock (2022) has formulated new hypotheses in an attempt to explain some of the observations discussed in this work. They can be summarised by following extracts from his work

– 'Neutrinos do not influence whether or not decay occurs. However, the direction of emission of decay products is influenced by the ambient neutrino flux, if and when decay occurs.'
– '[..] the key criterion for the detectability of decay variations is the directionality of the decay process. If directionality is conserved, oscillations may be detected, but if directionality is lost, oscillations will not be detected.'

– '[..] the directional characteristics of emission are preserved if propagation occurs purely in air, but the directional characteristics will be modified and perhaps lost if propagation occurs in a non-transparent medium.'
– 'This directionality relationship would be expected if neutrinos could directly influence the beta-decay process. However, such a direct influence seems unlikely in view of the exceedingly small cross-section for the influence of neutrinos on protons and electrons. [..] This suggests that some other particle or field (which we refer to hypothetically as a "neutrello") may be responsible for a coupling between neutrinos and beta decays.'
– '[..] the coupling is a collective process rather than a particle-particle process. [..] The collective interaction is attributable to the total electromagnetic field of all charged particles.'
– 'Concerning the concept of collectivity – that particles interact in a collective manner rather than through binary interactions – this concept can be checked by searching for evidence of a correlation between two experiments that are not co-located.'

Sturrock suggests execution of new experiments to test his hypotheses concerning

– the role of the medium, to determine whether gamma measurements are a function of the 'optical depth' of the source with respect to the detector.
– directionality by setting up two co-located measurements pointing in different directions
– collectivity by searching for evidence of a correlation between two experiments that are not co-located.
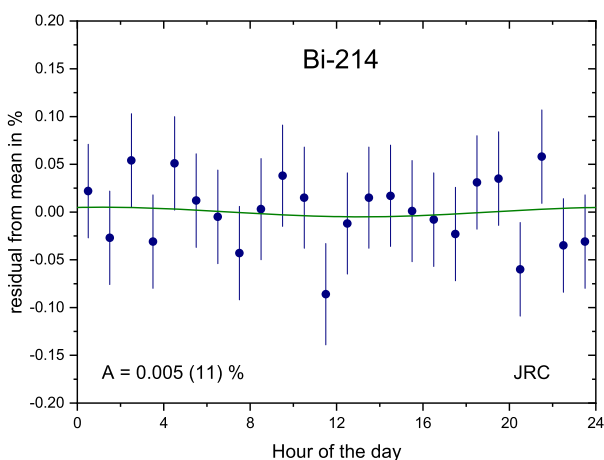
5.2 Directionality Experiments

As for the directionality hypothesis, it is known that the probability of emission of a particle or quantum of radiation from a single radioactive nucleus depends on the angle between the nuclear spin axis and the direction of emission. In normal conditions, the nuclei in a radioactive sample are randomly oriented, so there is no preferred direction of emission. Hence, the radiation pattern is isotropic. However, in a sample in which the orientation of the nuclei has been aligned, there can be preferred directions for emission.

Sturrock (2022) suggests that deexcitation radiation following beta decay on Earth is focussed downwards at noon (in the time zone of Israel!) due to cosmic neutrinos and upwards at midnight due to solar neutrinos. However, a century of daily practice in gamma-ray spectrometry has not resulted in findings of systematic changes in detection rates occurring with the time of the day. It is unimaginable that every γ-ray spectrometrist in the world would have missed a count rate boost of several percent, comparable to the daily peaks around noon in the radon measurements of Steinitz et al. (2018).

In fact, direct counterevidence to the directionality hypothesis has already been published by Pommé et al. (2018b, 2019b), but this was overlooked or ignored by Sturrock (2022), Sturrock et al. (2021a), even in a direct rebuttal of this work (Sturrock et al. 2018b). Examples were presented of repeated alpha-spectrometry and gamma-ray measurements of ^{226}Ra sources, containing ^{222}Ra and other progeny in secular equilibrium as decay products. At the JRC, a sealed ^{226}Ra source was measured at 14 cm distance (in air!) from a HPGe γ-ray detector, during 5.7 days at hourly intervals. Figure 13 shows the average residuals from the summed mean count rate as a function of the hour of the day for spectral regions containing γ-ray peaks from ^{214}Bi. There is no significant daily cycle within 0.011% uncertainty on the amplitude. The standard deviation of the data is close to the expected value from Poisson statistics. Therefore, there is no correlation between the position of the Sun or particular dark matter in space and the number of gamma rays measured within a fixed, small solid angle.

Fig. 13 Hourly average residuals from the mean count rates in γ-ray peaks from ^{214}Bi measured by γ-ray spectrometry of a sealed ^{226}Ra source at 14 cm distance from a HPGe detector

In another experiment, a decaying ^{54}Mn source was placed centrally in an air-filled gap of 4 cm between two NaI detectors, one at the top and the other at the bottom (Van Ammel et al. 2010). If the directionality rules also apply to electron capture decay, an anti-correlation between the decay rates measured in both detectors would be observed. The observed correlation factor was slightly positive ($\rho = 0.13$), possibly due to common influences by environmental parameters.

5.3 Influence of the Medium

According to Sturrock (2022), the LNGS radon experiments have demonstrated that the directionality effect should be clearly visible in air, and less in 'opaque' media. Since experiments do not confirm the first assertion within 0.01% standard deviation, an even higher reproducibility would be required to investigate the latter. Again, there are no reports from daily practice in nuclear spectrometry stating unusual decay rate activity variations from nuclei dissolved in different media, such as water or oil.

5.4 Collectivity Experiments

Decay rate measurements performed on sources from the same radionuclide have been inspected for 'collective' behaviour, i.e. correlation in time. No correlations appear in two identical alpha decay measurements of ^{209}Po running in parallel and showing residuals that are purely random in nature (Pommé and Benedik 2016). Half-life measurements of ^{177}Lu (Pommé et al. 2011) with different instruments show no immediate sign of bias with time, *a fortiori* also no synchronised effects. Half-life measurements of ^{54}Mn and ^{109}Cd (Van Ammel et al. 2010, 2011) did show a level of instability in the instruments, but no coherence in the residuals.

6 Conclusions

Periodograms of the Homestake, Gallex, GNO, Super Kamiokande I, and Borexino solar neutrino flux measurements show no statistically significant cycles other than the annual

modulation due to Earth-Sun distance. Radioactivity measurements are susceptible to environmental conditions at various degrees, depending on the metrology used. Direct measurements with gas detectors of beta particles emitted by external sources are notoriously susceptible to ambient temperature and humidity and therefore unfit for use in studies of hypothetical violations of the exponential-decay law. The most stable measurement techniques used at primary standardisation laboratories provide evidence that radioactive decay follows the exponential-decay law with high fidelity. There are no variations in the decay constants of radionuclides at a daily, monthly, annual or much longer timescale. There is no indication of a significant variation of decay rates attributable to a varying flux of solar or cosmic neutrinos. There is also no indication that radiation emitted in radioactive decay is preferentially aligned with the direction of the solar neutrino flux impinging on Earth.

The inference made by Sturrock that radioactivity is a probe for variations in solar or cosmic neutrino flux is based on invalid arguments. His claim regarding the existence of monthly cycles in solar neutrino flux data can be refuted on the basis of statistical significance criteria. The annual variations in the beta decay rate measurements referred to by Sturrock are not in phase with the solar neutrino flux on Earth, yet show significant correlation with ambient humidity. The so-called annual cycle in tritium decay claimed by Falkenberg is the result of bad experimental design and improper data analysis. The instabilities in the referenced radon decay rate measurements are largely caused by the free movement of radon gas in air along temperature gradients. The apparent instabilities in the GSI radon experiment, the 'flagship' of Sturrock's assertions regarding internal solar dynamics, are clearly driven by solar irradiance and rainfall. There is a total lack of coherence among the so-called significant cycles in solar neutrino flux and decay rate time series. Claims about solar and space science merely inferred from radioactive decay rate variations should be considered as unsubstantiated.

Declarations

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