THE EUROPEAN
PHYSICAL JOURNAL C

On the recent claim of correlation between radioactive decay rates and space weather

S. Pommé[a] , **K. Pelczar**

European Commission, Joint Research Centre (JRC), Geel, Belgium

Abstract In recent literature, several authors have challenged the validity of the exponential-decay law, based on observed variations in radioactive decay rate measurements beyond statistical accuracy. Tentative explanations have been sought in external interferences influencing the decay process, such as interactions of the nuclei with solar and cosmic neutrinos. Given the important implications of such statements on theoretical and practical level, one would expect that they are backed up with radionuclide metrology of the highest quality. In reality, they share the common traits of using poor metrology and incomplete uncertainty analysis with respect to the stability of the measurement technique. In this paper, new claims of correlations between decay rates and space weather are questioned.

1 Introduction

The exponential-decay law is a cornerstone of nuclear physics, the common measurement system of radioactivity, and numerous applications derived from it, including radiometric dating and nuclear dosimetry. It follows directly from quantum theory, which predicts invariable transition rate coefficients λ in most practical conditions, and its validity has been amply confirmed by experiment [1–3] with the most accurate measurement techniques used for primary [4] and secondary [5] standardisation of activity. As a result, international equivalence of radioactivity standards can be demonstrated at the 0.1% uncertainty level regardless of the time of measurement. Applying rigour in measurement conditions and data analysis [6,7], laboratories can reach consistency in half-life measurements at levels below 0.1–0.01%, as recently demonstrated in the case of ^{55}Fe [8,9] and ^{99m}Tc [10]. Repeated activity measurements with the most stable instruments show absence of cyclic perturbations down to 0.023–0.00023% in amplitude [3,11], when excluding the

susceptibility of the instrument to environmental conditions and using appropriate significance criteria [11,12]. In spite of the arguments in favour of the exponential-decay law, some authors have questioned the invariability of the decay constants [13–30]. Summaries of their claims and refutations by others have already been published in detail [3,31–34].

The most important class of experimental evidence pertains to activity measurements of beta emitters showing seasonal fluctuations of the order of 0.3%, with a periodicity of 1 year [13,16–19]. Whereas susceptibility of the measurement instrument to variations in temperature, humidity or radon concentration are plausible causes of the instabilities [32,35,36], the authors chose to make strong claims about decay being induced by solar or cosmic neutrinos interacting with the nuclei. Overwhelming counterevidence from various laboratories from four continents has proved that there are no systematic deviations from exponential decay above 0.01% level for α, β^-, β^+ and EC decay, and there is no coherence in amplitude and phase of annual cyclic effects in activity measurements across the globe [8,32–34,37–41]. None of the observed annual effects were in linear proportion with the seasonal variations of the solar neutrino flux resulting from the Earth–Sun distance. The decay of an alpha source in the Cassini spacecraft showed no dependency on distance variations with the Sun [42], and also radiochronology of meteorites was unaffected by heliocentric distance [43].

A second type of claim pertains to monthly cycles which have been associated with internal rotation of the Sun [21–24,26]. This was deduced from small peaks in periodograms of a few unstable activity measurements, and the assertion that the solar neutrino flux would reflect the rotation frequency of various zones in the solar interior. Radioactivity measurements were used as a tool to make claims about the dynamics of the solar interior [26]. However, thorough investigations of stable activity measurements of a suite of radionuclides showed that the existence of monthly

cycles could be excluded above the 0.01% level [3,8,11,44], thus invalidating the unjustified solar science derived from radioactivity. A complex scheme of daily and annual variations of radon decay rates inside a closed canister was presented as the best evidence of solar and cosmic neutrinos influencing the directionality of radiation emitted after neutrino-induced decay [20,26]. In response, it was shown that this interpretation was prone to many inconsistencies [45], and an alternative and more plausible explanation was given through the mobility of the radon along temperature gradients inside the air-filled canister [46,47]. The set-up was exposed to sunshine and rain, and the activity measurements were strongly correlated with outside weather conditions. Nevertheless, the authors categorically denied such environmental effects in favour of their inconsistent neutrino-based speculations.

A third type of claims relates decay rates with anomalies in space weather. A patent was issued to use neutrinos for space-weather forecast, since it was speculated that a sudden change in neutrino flux caused a dip in ^{54}Mn activity measurements 39 h before a solar flare crashed into Earth's magnetic field [15]. Attempts were made to correlate decay rate changes with neutrino-mediated effects from solar storms [25]. However, stable activity measurements demonstrated the invariability of the ^{54}Mn decay constant with time [33], and the absence of a correlation of activity with solar flares [48,49]. In addition, experiments performed in the vicinity of nuclear research reactors show no influence of the reactor neutrino flux on measured half-life values [50,51]. An experiment proved the independence of the ^{198}Au half-life of the source shape [52], thus contradicting a hypothesised self-induced decay effect.

Common denominators to the claims of violations of the exponential-decay law are the poor metrology on which they are based, the lack of an uncertainty evaluation of the attained experimental stability, and a cognitive bias towards facts contradicting the proposed conjecture. A striking example of metrological imperfection is the use of Geiger–Müller counters [19,27–29], arguably among the least reliable detectors of activity and therefore unsuited to test the invariability of the decay constants. Immunisation strategies have been devised to justify the use of such instruments [29,53,54]. Some authors [30] do not even bother to accurately describe the metrological conditions of their experiment to make fantastic new claims about radioactivity. Most of the counterevidence, on the other hand, was performed by experienced metrologists using superior detection techniques and showing awareness of the vulnerability of detector stability to external factors. This is witnessed by dedicated literature discussing factors contributing to the uncertainty budget for primary and secondary standardisation techniques [55–62].

With most claims being convincingly refuted, there are still recent papers by Milián-Sánchez et al. [27,29] and

Scholkmann et al. [28] to be addressed. These authors have measured background, capacitance and radioactive decay rates with a Geiger–Müller (GM) counter inside a 'modified Faraday cage' (MFC) over a short time period and assert correlations of these observables with 'space weather', *in casu* the 'geomagnetic activity' (GMA) and 'cosmic-ray activity' (CRA). As a more plausible explanation, we explore possible influences from ambient temperature and humidity.

2 Decay rate and space weather

Whereas the arguments in favour of variable decay constants are extremely weak compared to the evidence favouring the validity of the exponential-decay law, Milián-Sánchez et al. [29] still talk about a 'controversy' between both views. They continue referring to outdated work by Falkenberg [13] and Shnoll et al., even though its erroneous nature has already long been exposed (see e.g. [33] and [63], respectively). Also the claims for new physics by other authors have been invalidated, as discussed in the introduction, such that the radionuclide metrology community – represented in the Consultative Committee for Ionizing Radiation (CCRI), and the International Committee for Radionuclide Metrology (ICRM) – does not attach any consequence to their hypotheses.

Milián-Sánchez et al. [27–29] use GM counters for their activity measurements. Given the instability and lack of selectivity of such measurement tool, it comes as no surprise that the observed decay rate of a ^{226}Ra source varies within a 1% range over an experiment of 100 h in December 2014. The authors give no account of the uncertainty budget, as if they have perfect metrological control over the activity measurement, and therefore any statistically significant change in the decay rate is misinterpreted as evidence of a violation of the exponential-decay law. Their assertion is at variance with thousands of measurements in stable ionisation chambers at national metrology institutes showing that decay rates of ^{226}Ra check sources vary purely exponentially within 0.02% over decades [31,32]. As an example, the residuals of an exponential curve to ^{226}Ra source measurements in an ionisation chamber are shown for one decade in Fig. 1.

Next, they searched for space weather data that showed correlation with this small set of activity measurements. The Dcx index (http://dcx.oulu.fi) was chosen as a parameter which quantifies the state of the geomagnetic activity. In addition, they used the cosmic-ray induced neutron counts data (http://www.nmdb.eu/nest/search.php) to capture the cosmic ray activity. The paper provides no information as to which stations were selected, even though both time series differ qualitatively from one location to another. In a private communication, the authors confirmed that they combined Dcx data from 4 stations nearest to the experiment in Valencia, which should be Tamanrasset (1735 km), Iznik (2555 km),
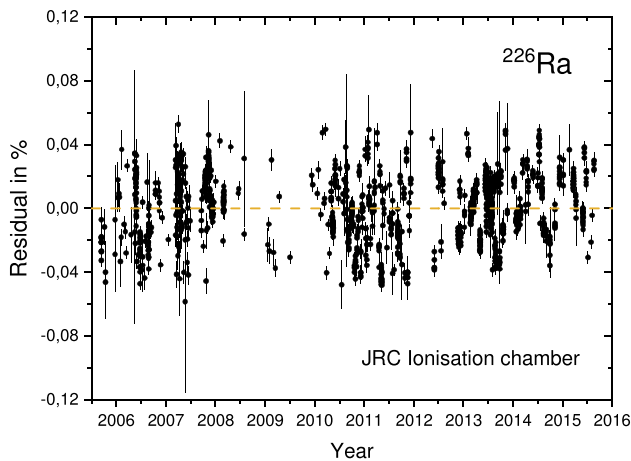
Fig. 1 Residuals in % of an exponential curve fitted to the ionisation current induced by a ^{226}Ra source in the IC1 ionisation chamber of the JRC, including ingrowth of decay progeny [32]. The error bars indicate sampling reproducibility only. The standard deviation of the residuals is 0.02%, which excludes variability of decay constants at a higher level

Mbour (3222 km) and Alma Ata (6229 km). They overlay the graphs of the activity measurements and the GMA and CRA indices (averaged in time and space), and notice a vague resemblance between the variations of the curves. The correlation coefficient between the ^{226}Ra decay rates and the space weather indices in that particular data set of December 2014 is of the order of -0.4 (GMA) and 0.4 (CRA). Add in a leap of faith that 'correlation means causality', and the influence of space weather on activity is 'demonstrated'.

To add some complexity to the story – or should we say irreproducibility? – the authors emphasize that these extraordinary conclusions were obtained when the GM detector and the source were placed inside a modified Faraday cage, which helps to 'transmit' or 'amplify' the GMA and CRA conditions from the outside to the GM sensors. The MFC stems from parascientific work on 'orgonomy' by W. Reich, and it consists of interleaving layers of cork and aluminium. By lack of a fully conductive enclosure, it is not expected to effectively block electromagnetic fields in its interior. According to the authors, the correlations with space weather occur when the decay rates measured outside the MFC are lower than inside. However, in a next data set taken over a period of 50 hours in February 2015, the correlation holds only with GMA and not with CRA. And lo and behold, in another experiment over a 140 h period in April 2015 all of the above led to zero correlation with GMA and CRA.

It is striking that the presented experimental data cover very short periods of 2–5 days only. As a result, the graphs show simple trends, which enhances the chance of obtaining relatively strong correlation effects with any other trending curve. Moreover, the data were obtained in 2014 and 2015 [27], and surprisingly their validity was not further tested

in a paper published five years later, in 2020 [29]. Continuation of these measurements for several years should not have been difficult and would have been much more conclusive with respect to proving true correlation and causality. No explanation was given for this lack of pursuit of ultimate proof, in spite of the spectacular claim of new physics and its important implications on nuclear physics and metrology.

Besides the ^{226}Ra source, tests were also performed with ^{204}Tl, ^{90}Sr/^{90}Y and ^{137}Cs sources. In summary, the correlations between the decay rates and the GMA and CRA indices were sometimes positive, negative or zero, as if there were no causality at all. The latter conclusion is most probably the only correct one. The literature abounds with examples of fortuitous correlations between unrelated observables [64] and authors have warned against 'spurious regression' of non-stationary data [65]. Any combination of two variables showing a simple trend with time will yield a positive or negative correlation, regardless of whether they share a common relationship.

3 Capacitance and space weather

In search of a metrological explanation for the variations of the decay rates in the Geiger–Müller counters, Milián-Sánchez et al. [27–29] measured the capacitance of the connection cable between the radiation detector and the scaler together with a class-I 10 nF multilayer ceramic capacitor of C0G (NP0) type, using 100 Hz, 10 kHz and 100 kHz sinusoidal test signals. The capacitance in cable and capacitor changed significantly each time when they were moved into a new position, either inside or outside the MFC. Whereas the decay rates may fluctuate by up to 5%, the capacitance in the cable varied by up to 1% and the capacitor up to 0.7%. The authors concluded that "capacitance variations were a factor that explained part of the decay measurements variability, but at the same time, this factor alone could not explain all the observed variability" [29]. This bold claim was made under the erroneous assumption that the registered count rates should vary linearly with the capacitance of a cable and capacitor. Reality is more complex, since decay rate changes will depend on various parameters, such as the shape of the radiation energy spectrum, signal threshold, noise baseline, pulse shape, and method of signal/noise discrimination, to name a few.

A direct comparison of capacitance with the GMA/CRA indices generally showed no correlation. Nevertheless, the authors mention that a 'moderate geomagnetic storm' coincides with the moment in which they reposition the capacitor and observe a relatively large jump in capacitance. They hint that an 'intense geomagnetic storm' precedes a steep drop in the capacitance at 100 Hz. Over a period of about a month (14 March – 14 April 2015), there is a marked similarity in the

shape of the capacitance and neutron time series (comprising of a small and larger hump followed by a broad hump). The authors come to the conclusion that, under certain conditions, there is a causal relationship between the GMA/CRA indices and capacity, just as it was the case with the decay rate measurements. If we indulge the authors in this conclusion, it would seem logical to conclude that the observed anomalies in the decay rates would be of metrological nature and not attributable to changes in the decay constants of the radionuclides. After all, the capacitance measurements are not related to radioactivity at all. The authors do not present a full explanation of their observations, but announce to look into dielectric polarizability as root cause.

4 Decay rates and terrestrial weather

In a sound approach, the instability of the GM counter should in the first place be investigated through known susceptibility of electronics to environmental factors and external interferences. If the circuit is poorly isolated from outside influences, those influences behave like circuit elements. Sometimes, these show up as performance variations that depend on where one holds the instrument, or whether there's a metal surface nearby. The GM counter, a transmission cable, or some components in the scaler may change their properties because of external parameters. The MFC may act as an antenna for electromagnetic signals and can pass on RF noise by capacitive coupling. The dielectric constant of cork depends on frequency, temperature, and humidity [66]. A temperature variation of 5 degrees in a resistor responsible for gain setting in the scaler suffices to change the amplification by 0.2 dB, which in turn corresponds to 2% change in the output voltage. The threshold level in the scaler is set by a single potentiometer referenced directly to the power line. The accuracy of the scaler linearity, reported by the manufacturer, is of the order of 2% [67]. Also, corrosion of contacts can play a role, dust settling on BNC plugs, and Kelvin potentials in the grounding of the apparatus, in conjunction with influences by temperature and humidity. And with respect to decay rates, it is of interest to know how the source-detector geometry was reproduced when moving the GM counter in and out of the cage.

These and other considerations are at variance with the statement by Milián-Sánchez et al. [27] that "GM counters are very stable and robust detection systems". According to their investigations, "changes in decay rates do not correspond to changes in air density and in ambient temperature". Some of these parameters cannot be verified from a distance, but when it comes to testing the impact of environmental conditions on the electronic equipment, there are historical temperature, air humidity and pressure data available on the internet [68]. In Fig. 2, the air humidity in the Valencia
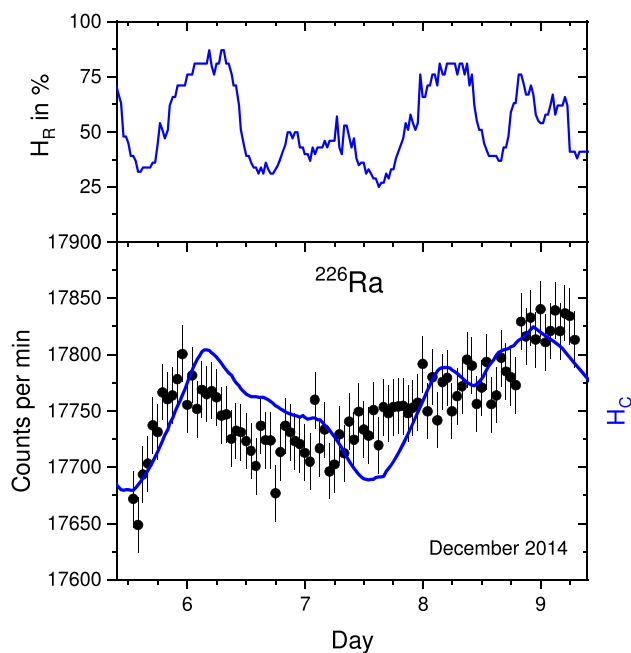

Fig. 2 Relative humidity in the Valencia region (top) in the period 5-9 Dec 2014 [68]. Qualitative comparison (bottom) of measured ^{226}Ra decay rates [27–29] with the accumulated-humidity model $H_C(t; \bar{H}_R = 50\%, \Delta t = -7\,\text{h})$ in Eq. 1

region is plotted between 5 and 9 December 2014, and in comparison the measured ^{226}Ra decay rates are shown in the graph below. It is striking that, on midnight of 5 December, the marked peak in the decay rates coincides with a peak in air humidity. There seems to be a correlation between lows and highs in both curves, even though the decay rate curve is smoother.

A simple moisture accumulation model was devised to investigate this correlation qualitatively. The relative air humidity data series, $H_R(t)$, sequenced in steps of half an hour, was summed (starting from at least one day before the decay rate measurements) and a convenient medium value $\bar{H}_R$ was subtracted to realign the baseline

$$H_C(t) = \sum_{t' < t - \Delta t} (H_R(t') - \bar{H}_R) \quad (1)$$

No hard claims are made about the physical rigour of this toy model, but it allows to smooth out the humidity data in time (by accumulation), to adjust the baseline (by adapting $\bar{H}_R$ to preceding conditions) and to perform a time shift (by changing Δt). In Fig. 2, the model humidity $H_C(t; \bar{H}_R = 50\%, \Delta t = -7\,\text{h})$ is overlaid on the ^{226}Ra decay rates graph, using a matching scale. It is striking how well the shape of the humidity model output matches with the local structures in the decay rates. Surprisingly, the timing matches best with a negative delay, $\Delta t = -7h$, which counteracts the time delay ensuing from integration of humidity data and somewhat contradicts the initial idea of a delayed
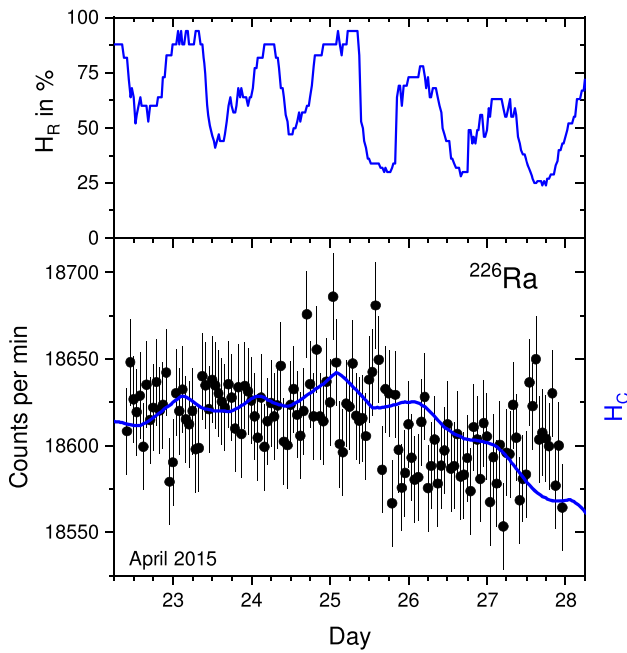
Fig. 3 Relative humidity in the Valencia region (top) in the period 22–27 Apr 2015 [68]. Qualitative comparison (bottom) of measured ^{226}Ra decay rates [27,29] with the accumulated-humidity model $H_C(t; \bar{H}_R = 66\%, \Delta t = -7\,\text{h})$ in Eq. 1
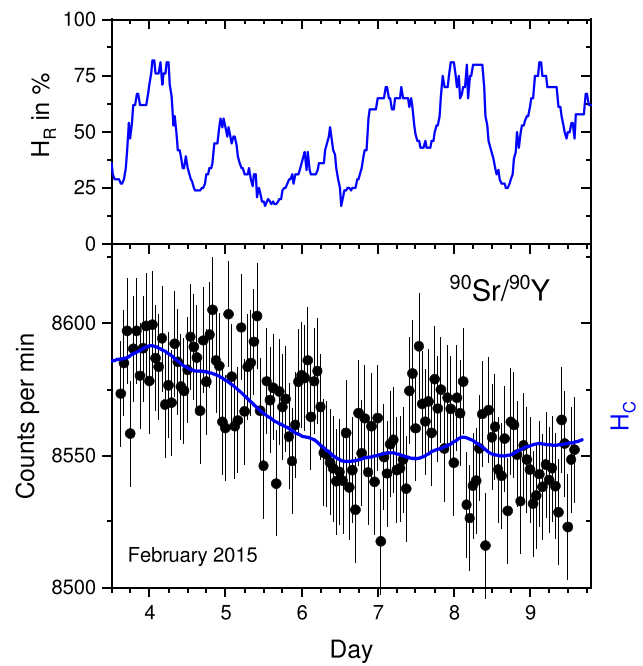

Fig. 4 Relative humidity in the Valencia region (top) in the period 3–9 Feb 2015 [68]. Qualitative comparison (bottom) of measured ^{90}Sr/^{90}Y decay rates [27,29] with the accumulated-humidity model $H_C(t; \bar{H}_R = 56\%, \Delta t = -7\,\text{h})$ in Eq. 1

effect due to humidity accumulation. It may also partly compensate a difference in time base between both data sets, or reflect possible prior changes in the local temperature.

The same model was applied on other decay rate data sets, and again correlations seem to appear. Figure 3 shows the ^{226}Ra decay rates measured from 22 to 27 April 2015. The constant decay rate in the first days, is followed by a negative slope and the same trend is present in the air humidity data. The model humidity $H_C(t; \bar{H}_R = 66\%, \Delta t = -7\,\text{h})$ captures some of the subtle wobbles in the decay rates and the succession of a flat part and a downward slope. The model $H_C(t; \bar{H}_R = 56\%, \Delta t = -7\,\text{h})$ also captures quite well the activity measurements of the ^{90}Sr/^{90}Y source between 3 and 9 February 2015, as shown in Fig. 4. The correlation between decay rate and air humidity is particularly remarkable with respect to the fall of the baseline during two dry days on 5–6 February. And finally, the ^{240}Tl decay rates in Fig. 5 appear to be proportional with the air humidity data, albeit that the data set is small.

For completeness, all the graphs in Ref. [27] were compared with the humidity accumulation model and a qualitative resemblance generally applied, even in seemingly 'uneventful' graphs. The background measurements from 19–22 December 2014 in Fig. 6 were performed during conditions of high ambient humidity, initially close to 100% and somewhat lower in the second half of the measurement period. This modest drying out effect appears to coincide with a subtle lowering of the background count rate. A subtle
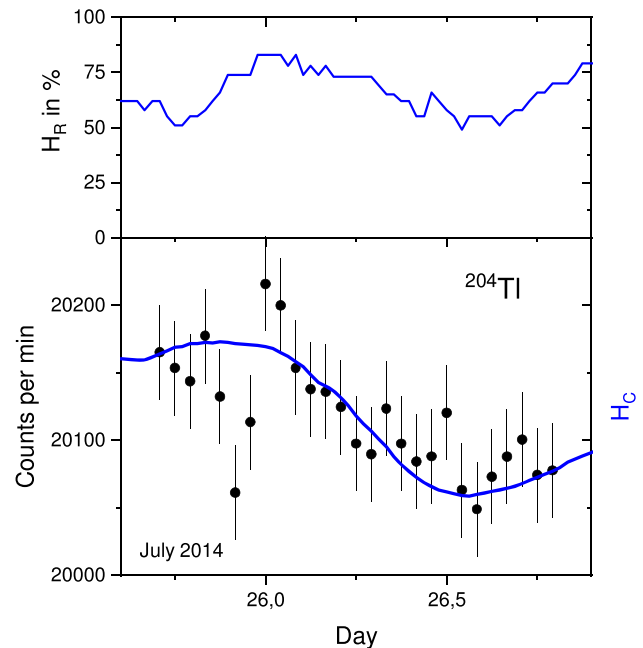

Fig. 5 Relative humidity in the Valencia region (top) in the period 25–26 July 2014 [68]. Qualitative comparison (bottom) of measured ^{204}Tl decay rates [27,29] with the accumulated-humidity model $H_C(t; \bar{H}_R = 75\%, \Delta t = -7\,\text{h})$ in Eq. 1

rise in another background measurement on 18–19 December 2014 is compatible with a rise in humidity. Natural activity in the surrounding materials – e.g. the aluminium sheets of
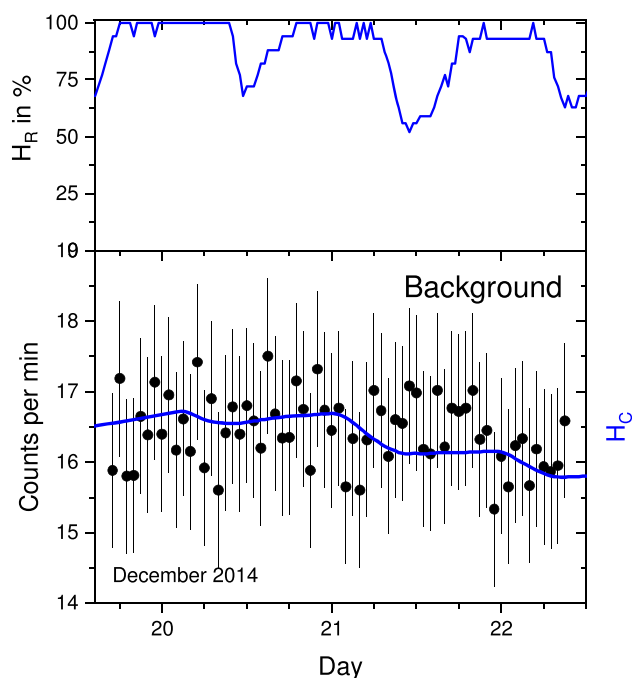
Fig. 6 Relative humidity in the Valencia region (top) in the period 19–22 Dec 2014 [68]. Qualitative comparison (bottom) of measured background rates [27,29] with the accumulated-humidity model $H_C(t; \bar{H}_R = 92\%, \Delta t = -7\,\text{h})$ in Eq. 1

Fig. 7 Relative humidity in the Valencia region (top) in the period 16–17 Dec 2014 [68]. Qualitative comparison (bottom) of measured ^{226}Ra decay rates [27,29] with the accumulated-humidity model $H_C(t; \bar{H}_R = 66\%, \Delta t = -7\,\text{h})$ in Eq. 1. The indicators IN and OUT refer to the position of the detector inside or outside of the MFC

the MFC, often rich in Th and Ra impurities – may have contributed to reported differences in background rates inside the MFC as compared to outside.

A short test on 16–17 December 2014, involving a ^{226}Ra source first measured outside and then inside the MFC, shows a jump not explained by the humidity model (Fig. 7). This may point to changes in source-detector geometry, capacitance in the cable and connector, or electronic interference, possibly mediated by humidity in the cork layers (capacitive coupling of noise), in high-voltage cable insulation (current leakage), or involuntary human interaction with the set-up. However, after 2 h of acclimatisation inside the cage, the time dependence of the decay rates series is consistent again with the humidity model. A more elaborate repetition of the test in January 2015, shows again jumps when moving the detector in and out of the cage. It is interesting to note that they may be in part associated with changes in humidity, as suggested by the model in Fig. 8.

In spite of the simplicity of the toy model in Eq. 1, the striking correlation of the humidity trendlines with the measured decay rates with the GM counter make a strong case for the hypothesis that the set-up was susceptible to the local humidity/temperature effects. Whereas the correlations with 'space weather' in Ref. [29] were mostly spurious (the regression randomly being positive, negative, or zero), the correlation of detector output with humidity turns out to be consistently positive. Hence, it appears that there is no reasonable ground
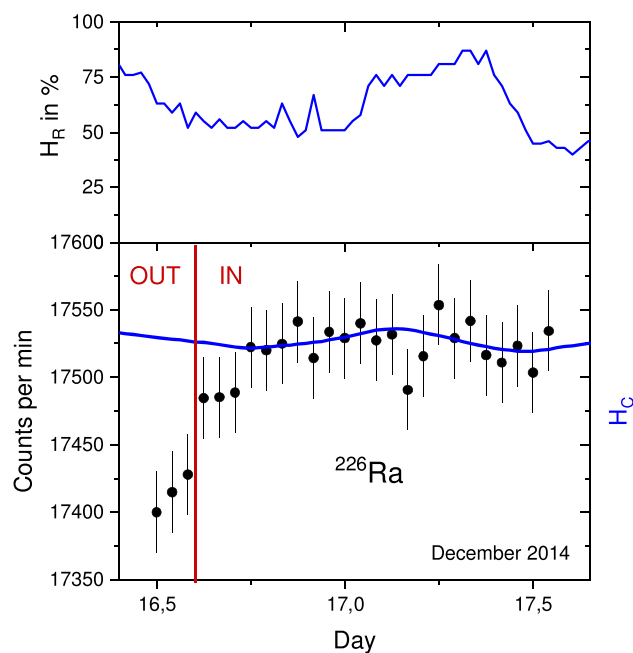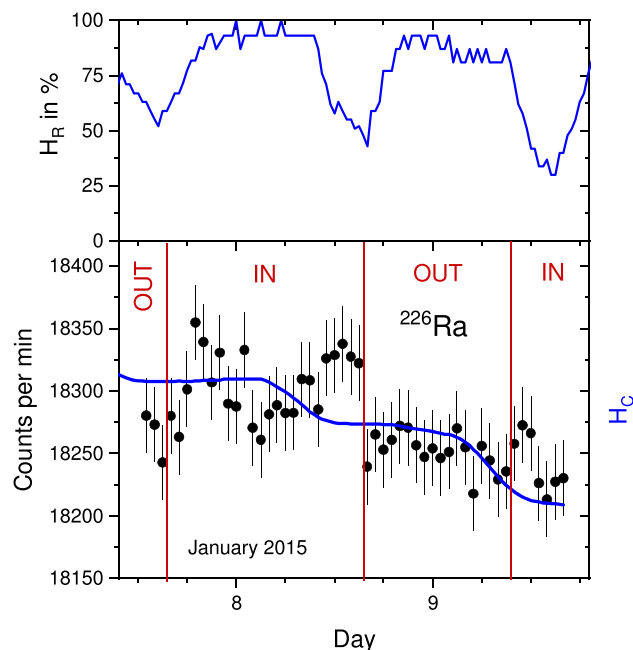

Fig. 8 Relative humidity in the Valencia region (top) in the period 7–9 Jan 2015 [68]. Qualitative comparison (bottom) of measured ^{226}Ra decay rates [27,29] with the accumulated-humidity model $H_C(t; \bar{H}_R = 92\%, \Delta t = -7\,\text{h})$ in Eq. 1. The indicators IN and OUT refer to the position of the detector inside or outside of the MFC
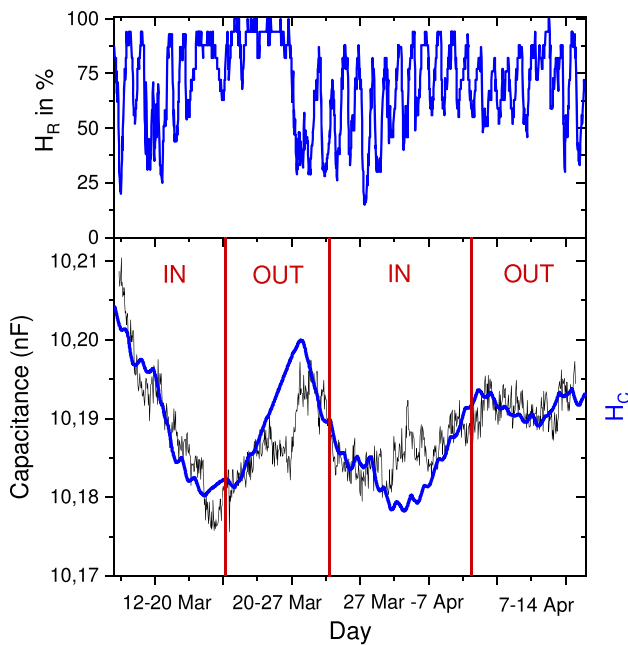
Fig. 9 Relative humidity in the Valencia region (top) in the period 12 Mar–14 Apr 2015 [68]. Plot of the measured capacitance of the detector cable and reference capacitor [27] (thin line) overlaid with the result of a humidity-accumulation model using data from a Valencia weather station [68] (bottom). In the four periods, indicating different placement of the capacitor (inside and outside of the MFC), the model parameters values $\Delta t = +16\,$h and $\bar{H}_R = 82\%$, 73%, 62%, and 72% were used, respectively

to claim that radioactivity is influenced by space weather. The mythical role of the MFC as a mediator for space weather can be catalogued as pseudoscience, which is also the corner where it came from.

5 Capacitance and terrestrial weather

The humidity model was additionally applied to the capacitance measurements performed from 12 March to 14 April. In Fig. 9, an overlay is shown of the accumulated humidity on top of the graph of the measured capacitance values as a function of time [27]. Suitable parameter values for $\bar{H}_R$ were chosen in the four successive periods in which the capacitor was taken inside and out of the cage. The steep descent in capacitance in the first period (12–20 March) coincided with a relative dry period, whereas the subsequent rise happened in a very wet period (20–27 March). The local bump around 2 April is not reproduced by the model; It may have been caused by local precipitation near the laboratory that was not captured at the Valencia weather station [68]. The wobbles in the capacitance data in the fourth period (7–14 April) are well reproduced by the humidity model.

It is fair to conclude that ambient humidity, or correlated weather conditions, must have played a significant role in the capacitance measurements. However, it was already mentioned that the same capacitance data set (Fig. 9) showed a marked resemblance with the activity of cosmic-ray induced neutrons [29]. A similar resemblance was reported in background activity measurements (Fig. 6) [29]. These correlations can be explained as resulting from a common influence. In Europe, there appears to be a statistically significant link between low-cloud coverage and cosmic-ray (CR) intensity, i.e. the energy-integrated flux commonly measured by ground-based neutron monitors [69]. At the same time, the cloud cover is positively correlated with relative humidity at ground level. It is noteworthy that the CR flux on Earth is modulated also by the slowly changing geomagnetic field, which does not allow the least energetic – but most abundant – CR particles to impinge on the Earth [69].

6 Conclusions

The work of Milián-Sánchez et al. [27–29] falls short in aspects of metrological rigour: the detector set-up is notoriously unstable, plausible causes of the detector instability were insufficiently investigated, no uncertainty budget was provided, insufficient measurements were performed to confirm or disproof correlations between decay rates and space weather, invalid conclusions were drawn from spurious regression on limited data sets, and no consistency was reached in farfetched theories implying new physics. Evidence provided in this work shows that there is good reason to believe that "terrestrial weather" influenced the electronics. There is no ground whatsoever to infer that "cosmic weather" influences decay constants. This is compatible with the absence of violations of the exponential decay law in high-precision activity measurements.

It is not the first time that unrealistic theories have been launched on the feeble shoulders of flawed metrology. Although science is always open to new ideas, the power of the argument lies in the quality of the empirical test. Good metrology entails a detailed understanding of the uncertainty budget [70], and good communication thereof. The conclusions of Lindstrom [71] with respect to the roles of the authors, reviewers and editors of scientific journals remain essential for producing believable science.

References

1. G.T. Emery, Annu. Rev. Nucl. Sci. **22**, 165–202 (1972)
2. H.-P. Hahn, H.-J. Born, J.I. Kim, Radiochim. Acta **23**, 23–37 (1976)
3. S. Pommé, H. Stroh, K. Kossert, O. Nähle, J.D. Keightley, K.M. Ferreira, L. Verheyen, M. Bruggeman, Appl. Radiat. Isot **134**, 6–12 (2017)
4. S. Pommé, Metrologia **44**, S17–S26 (2007)
5. H. Schrader, Metrologia **44**, S53–S66 (2007)
6. S. Pommé, J. Camps, R. Van Ammel, J. Paepen, J. Radioanal. Nucl. Chem. **276**, 335–339 (2008)
7. S. Pommé, Metrologia **52**, S51–S65 (2015)
8. S. Pommé, H. Stroh, R. Van Ammel, Appl. Radiat. Isot. **148**, 27–34 (2019)
9. K. Kossert, Appl. Radiat. Isot. **155**, 108931 (2020)
10. S. Pommé, Appl. Radiat. Isot. **148**, 171–178 (2018)
11. S. Pommé, T. De Hauwere, Nucl. Instrum. Methods A **956**, 163377 (2020)
12. S. Pommé, Nucl. Instrum. Methods A **968**, 163933 (2020)
13. E.D. Falkenberg, Apeiron **8**, 32–45 (2001)
14. Y.A. Baurov, Y.G. Sobolev, Y.V. Ryabov, V.F. Kushniruk, Phys. Atom. Nucl. **70**, 1825–1835 (2007)
15. J.H. Jenkins, E. Fischbach, Astropart. Phys. **31**, 407–11 (2009)
16. J.H. Jenkins et al., Astropart. Phys. **32**, 42–46 (2009)
17. E. Fischbach et al., Space Sci. Rev. **145**, 285–335 (2009)
18. E. Fischbach, J. H. Jenkins, P. H. Sturrock, arXiv:1106.1470 (2011)
19. A.G. Parkhomov, J. Mod. Phys. **2**, 1310–1317 (2011)
20. G. Steinitz, O. Piatibratova, P. Kotlarsky, J. Environ. Radiat. **102**, 749–765 (2011)
21. P.A. Sturrock et al., Astropart. Phys. **42**, 62–69 (2013)
22. Y.A. Baurov, Y.G. Sobolev, Y.V. Ryabov, Am. J. Astron. Astrophys. **2**, 8–19 (2014)
23. P. A. Sturrock, E. Fischbach, A. G. Parkhomov, J. D. Scargle, G. Steinitz, arXiv:1510.05996 (2015)
24. P.A. Sturrock, E. Fischbach, J.D. Scargle, Solar Phys. **291**, 3467–3484 (2016)
25. T. Mohsinally, S. Fancher, M. Czerny, E. Fischbach, J.T. Gruenwald, J. Heim, J.H. Jenkins, Astropart. Phys. **75**, 29–37 (2016)
26. P.A. Sturrock, G. Steinitz, E. Fischbach, Astropart. Phys. **100**, 1–12 (2018)
27. V. Milián-Sánchez, A. Mocholí-Salcedo, C. Milián, V.A. Kolombet, G. Verdú, Nucl. Instrum. Methods A **828**, 210–228 (2016)
28. F. Scholkmann et al., Europhys. Lett. **117**, 62002 (2017)
29. V. Milián-Sánchez et al., Sci. Rep. **10**, 8525 (2020)
30. S.V. Adamenko et al., Prog. Phys. **16**, 67–70 (2020)
31. S. Pommé et al., Phys. Lett. B **761**, 281–286 (2016)
32. S. Pommé et al., Metrologia **54**, 1–18 (2017)
33. S. Pommé et al., Metrologia **54**, 19–35 (2017)
34. S. Pommé et al., Metrologia **54**, 36–50 (2017)
35. O. Nähle, K. Kossert, Astropart. Phys. **66**, 8–10 (2015)
36. H. Schrader, Appl. Radiat. Isot. **114**, 202–213 (2016)
37. E.B. Norman, E. Browne, H.A. Shugart, T.H. Joshi, R.B. Firestone, Astropart. Phys. **31**, 135–137 (2009)
38. J.C. Hardy, J.R. Goodwin, V.E. Iacob, Appl. Radiat. Isot. **70**, 1931–1933 (2012)
39. K. Kossert, O.J. Nähle, Astropart. Phys. **55**, 33–36 (2014)
40. K. Kossert, O.J. Nähle, Astropart. Phys. **69**, 18–23 (2015)
41. E. Bellotti, C. Broggini, G. Di Carlo, M. Laubenstein, R. Menegazzo, Phys. Lett. B **743**, 526–530 (2015)
42. P.S. Cooper, Astropart. Phys. **31**, 267–269 (2009)
43. M.M.M. Meier, R. Wieler, Astropart. Phys. **55**, 63–75 (2014)
44. S. Pommé, K. Kossert, O. Nähle, Sol. Phys. **292**, 162 (2017)
45. S. Pommé, G. Lutter, M. Marouli, K. Kossert, O. Nähle, Astropart. Phys. **107**, 22–25 (2019)
46. S. Pommé, G. Lutter, M. Marouli, K. Kossert, O. Nähle, Astropart. Phys. **97**, 38–45 (2018)
47. S. Pommé, Eur. Phys. J. C. **79**, 73 (pp. 9) (2019)
48. E. Bellotti, C. Broggini, G. Di Carlo, M. Laubenstein, R. Menegazzo, Phys. Lett. B **720**, 116–119 (2013)
49. E. Bellotti, C. Broggini, G. Di Carlo, M. Laubenstein, R. Menegazzo, Phys. Lett. B **780**, 61–65 (2017)
50. R.J. de Meijer, M. Blaauw, F.D. Smit, Appl. Radiat. Isot. **69**, 320–326 (2011)
51. V.E. Barnes et al., Appl. Radiat. Isot. **149**, 182–199 (2019)
52. R.M. Lindstrom, E. Fischbach, J.B. Buncher, J.H. Jenkins, A. Yue, Nucl. Instrum. Methods A **659**, 269–271 (2011). Erratum **664**, 231
53. E.K. Elmaghraby, Prog. Phys. **13**, 150–155 (2017)
54. A.G. Parkhomov, J. Mod. Phys. **9**, 1617–1632 (2018)
55. S. Pommé, R. Fitzgerald, J. Keightley, Metrologia **52**, S3–S17 (2015)
56. S. Pommé, Metrologia **52**, S73–S85 (2015)
57. R. Fitzgerald, C. Bailat, C. Bobin, J. Keightley, Metrologia **52**, S86–S96 (2015)
58. C. Thiam, C. Bobin, F.J. Maringer, V. Peyres, S. Pommé, Metrologia **52**, S97–S107 (2015)
59. M.N. Amiot et al., Metrologia **52**, S108–S122 (2015)
60. M.-C. Lépy, A. Pearce, O. Sima, Metrologia **52**, S123–S145 (2015)
61. S. Pommé, Metrologia **52**, S146–S155 (2015)
62. K. Kossert, R. Broda, P. Cassette, G. Ratel, B. Zimmerman, Metrologia **52**, S172–S190 (2015)
63. M.P. Silverman, W. Strange, Europhys. Lett. **87**, 32001 (2009)
64. T. Vigen, *Spurious Correlations* (Hachette Books. ISBN 9780316339438, 2015) https://www.tylervigen.com/spurious-correlations
65. C.W.J. Granger, P. Newbold, J. Econom. **2**, 111–120 (1974)
66. J.N. Marat-Mendes, E.R. Neagu, Ferroelectrics **294**, 123–131 (2003)
67. Ludlum Measurements, Inc., Information sheet of the Model 2200 general purpose scaler/ratemeter. https://ludlums.com/images/data_sheets/M2200.pdf
68. Time and Date AS, Valencia Weather History, https://www.timeanddate.com/weather/spain/valencia/historic
69. I.G. Usoskin, G.A. Kovaltsov, C. R. Geosci. **340**, 441–450 (2008)
70. S. Pommé, Metrologia **53**, S55–S64 (2016)
71. R.M. Lindstrom, J. Radioanal. Nucl. Chem. **311**, 1019–1022 (2017)