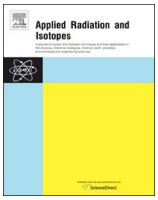
Applied Radiation and Isotopes 134 (2018) 6–12

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso



Is decay constant?

S. Pommé[a,*], H. Stroh[a], T. Altzitzoglou[a], J. Paepen[a], R. Van Ammel[a], K. Kossert[b], O. Nähle[b], J.D. Keightley[c], K.M. Ferreira[c], L. Verheyen[d], M. Bruggeman[d]

[a] European Commission, Joint Research Centre (JRC), Directorate for Nuclear Safety and Security, Retieseweg 111, B-2440 Geel, Belgium
[b] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[c] National Physical Laboratory (NPL), Hampton Road, Teddington, Middlesex TW11 OLW, UK
[d] Belgian Nuclear Research Centre (SCK•CEN), Boeretang 200, B-2400 Mol, Belgium

HIGHLIGHTS

- Repeatedly measured decay rates of radionuclides.
- No cycles between 1 and 20 year^{-1} in residuals from exponential decay.
- No evidence of variable decay constants due to solar neutrinos.
- No effect from 11.1-year solar cycle on decay rate.

ARTICLE INFO

Keywords:
Half-life
Decay constant
Radioactivity
Solar cycle
Neutrino
Cognitive bias

ABSTRACT

Some authors have raised doubt about the invariability of decay constants, which would invalidate the exponential-decay law and the foundation on which the common measurement system for radioactivity is based. Claims were made about a new interaction – the fifth force – by which neutrinos could affect decay constants, thus predicting changes in decay rates in correlation with the variations of the solar neutrino flux. Their argument is based on the observation of permille-sized annual modulations in particular decay rate measurements, as well as transient oscillations at frequencies near 11 year^{-1} and 12.7 year^{-1} which they speculatively associate with dynamics of the solar interior. In this work, 12 data sets of precise long-term decay rate measurements have been investigated for the presence of systematic modulations at frequencies between 0.08 and 20 year^{-1}. Besides small annual effects, no common oscillations could be observed among α, β^-, β^+ or EC decaying nuclides. The amplitudes of fitted oscillations to residuals from exponential decay do not exceed 3 times their standard uncertainty, which varies from 0.00023 % to 0.023 %. This contradicts the assertion that 'neutrino-induced' beta decay provides information about the deep solar interior.

1. Introduction

1.1. The exponential-decay law

According to quantum theory, radioactive decay is a stochastic process at the level of single atoms, in that it is impossible to predict when a particular atom will decay regardless of how long the atom has existed. Under certain assumptions, the transition rate coefficient λ can be derived from the Fermi Golden Rule and is constant in time. The survival probability of a quantum state takes the shape of an exponential. Violations of the exponential-decay law are theoretically expected at extremely short ($\lambda t \ll 1$) and extremely long times ($\lambda t > > 1$). Quantum Zeno and anti-Zeno effects are short-time deviations in which decay slows down or speeds up, respectively, due to interrogation of the quantum system (Chaudhry, 2016). At long times, power law deviations are expected to kick in when the width of the energy distribution is large compared to the released energy (Rothe, 2006). In the particular case of radioactive decay, the necessary conditions may be so extreme – $\lambda t < 10^{-14}$ and $\lambda t > 71$ (Semkow, 2007) – that they are in experimentally inaccessible time domains. Empirical evidence (Norman et al., 1988, 1995) complies with the exponential-decay law, which is the cornerstone on which the common measurement system of radioactivity is built.

The exponential decay law can also be derived from probabilistic arguments. Mathematically the constancy of the decay rate coefficient λ is a necessary as well as sufficient condition for exponential decay. Each

---

[*] Corresponding author.
E-mail address: stefaan.pomme@ec.europa.eu (S. Pommé).

http://dx.doi.org/10.1016/j.apradiso.2017.09.002
Received 13 March 2017; Received in revised form 12 June 2017; Accepted 4 September 2017

radionuclide has a particular decay constant, or equivalently a characteristic half-life period – $T_{1/2} = \ln(2)/\lambda$ – over which the probability for decay is 50 %. Applied to a large number N of atoms, the expectation value of the decay rate is $\rho(t) = \lambda N(t)$ and the number of remaining atoms as well as the activity decreases exponentially. As a result of the randomness of decay, the time intervals between successive decays follow an exponential distribution and non-selective counting of decays is governed by Poisson statistics. These properties are confirmed by counting experiments when properly taking into account the well-understood impact of pulse pileup and characteristic dead time of nuclear counters (ICRU, 1994; Pommé et al., 2015). The reader is referred to (Semkow, 2007) for a review of the exponential decay law and nuclear statistics.

1.2. Foundation of the measurement system

Setting up a common measurement system (Judge et al., 2014) through the SI-derived unit, the becquerel (s^{-1}), and establishing international equivalence among national standards relies entirely on the invariability of decay constants in space and time (aside from time dilatation due to relativistic speed or a strong gravitational field). Aliquots of a radionuclide in solution are standardised for massic activity by means of primary standardisation techniques (Pommé, 2007) and international equivalence is demonstrated by direct comparison or indirectly through a measurement of the ionisation current in a transfer instrument such as the Système International de Référence (SIR) (Ratel, 2007). Due to the stability of the SIR ionisation chambers in use since 1976, the equivalence of standardisations performed over a period of 4 decades can be demonstrated within parts per thousand or 'permille' level accuracy (BIPM, 2017). The example of ^{60}Co is shown in Fig. 1. Whereas historical data show some cases of inconsistency at permille level due to incomplete uncertainty estimation (Pommé and Keightley, 2015; Pommé, 2006, 2016), there is no coherent proof of changes in the decay constants. Also half-life measurements performed over a century in different laboratories show occasional discrepancies, but with an increased attention for uncertainty evaluation (Pommé, 2015) there is a growing convergence of published half-life values at a sub-permille level (DDEP, 2017). Historical data for ^{198}Au are shown in Fig. 2.

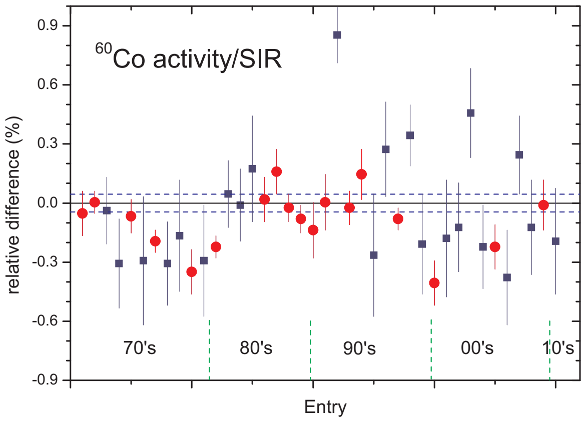


Fig. 1. Relative difference in ^{60}Co activity standards from 21 national metrology institutes and measured in the SIR at the BIPM relative to 1 out of 4 ^{226}Ra reference sources (Michotte, 2017). The graph shows all submissions with a stated standard uncertainty below 0.33 %: they have a standard deviation of 0.22 % (excluding one outlier). The data with less than 0.15 % uncertainty (red circles) have 0.15 % standard deviation. The data are arranged according to year of submission, i.e. between 1976 and 2014. The decades are indicated in the bottom of the graph. The lines correspond to the reference value and its standard uncertainty. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

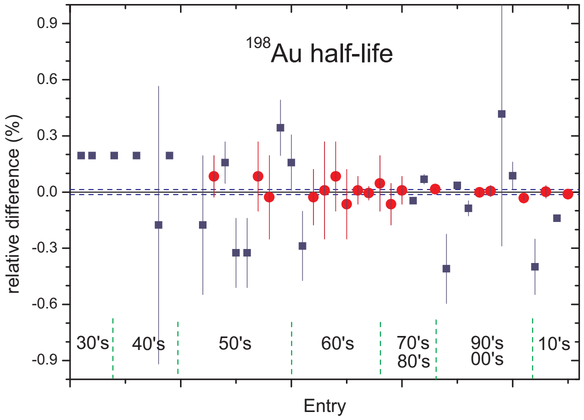


Fig. 2. Relative difference between measured half-life values of ^{198}Au arranged according to year of publication, i.e. between 1935 and 2012 (Chen et al., 2011; Hardy et al., 2012). The decades are indicated in the bottom of the graph. The standard deviation of the best matching data (red circles) with the power-moderated mean (Pommé and Keightley, 2015) of 2.6948(4) d is 0.045 %. The lines correspond to the reference value and its standard uncertainty. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our knowledge of the time scale of human evolution, the age of Earth and the solar system, and various geological and biological milestones is based on radioactivity. Chronometry through the decays of long-lived radionuclides yields mutually consistent dates, furthermore backed up with other dating techniques such as dendrochronology, ice core dating and historical records (Currie, 2004; Renne et al., 1997). Cross-section data from the Oklo natural nuclear reactor (Fujii et al., 2000) and absorption lines of distant quasars (Srianand et al., 2004) demonstrate that the fine-structure constant, which has an impact on radioactive decay rates, has not changed in 2–10 billion years. Supernovae up to billions of light-years away produced isotopes emitting gamma rays with frequencies and fading rates that are predictable according to present decay rates (Prantzos, 1999). Decay constants are also invariable under changes in pressure and temperature (Emery, 1972), except potentially at extreme conditions relevant to stellar nucleosynthesis and cosmochronology (Atanasov et al., 2015). Electron capture is inhibited in fully ionized atoms, but the atoms can become unstable for bound-state β decay to K and L shells, thus enhancing β^- decay in stellar interiors and affecting galactic age estimation (Bosch et al., 1996). Extreme pressure in core-collapse supernovae suppresses beta decay (as the increasing Fermi energy of the electrons blocks the available phase space for the decay), which is an enabling factor in the r-process responsible for production of heavy nuclei (Janka et al., 2007). Electron capture and internal conversion are slightly sensitive to chemical and environmental effects that change the electronic density in the atom, as this affects the availability of the s-state electrons to participate in the decay process (Norman et al., 2001).

1.3. Claims of variable decay constants

Fischbach et al. (2011) have made claims about a new interaction – the fifth force – by which neutrinos could affect decay constants, thus predicting changes in decay rates in correlation with variations of the solar neutrino flux. Other hypotheses have been launched finding against constancy of decay rates, e.g. Parkhomov (2011) suggesting that periodic changes in beta radioactivity is due to interactions with slow cosmic neutrinos from dark matter. Their claims were based on the observation of permille-sized annual modulations in hand-picked unstable decay rate measurements, which they tried to link with neutrino flux changes in phase with the orbital distance of Earth to the Sun. Various metrologists have produced convincing counterevidence showing that decay constants are insensitive to the Earth–Sun distance typically within the 10^{-5}–10^{-6} level, irrespective of the type of radioactive decay. The reader is referred to (Pommé et al., 2016, 2017a, b, c) for a more elaborate discussion and references on the subject.

Fischbach et al. have progressively weakened their claims when