Anomalies in Radioactive Decay Rates:
A Bibliography of Measurements and Theory

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7 December 2020

Abstract. Knowledge of the decay rates (or half-lives) of radioisotopes is critical in many fields, including medicine, archeology, and nuclear physics, to name just a few. Central to the many uses of radioisotopes is the belief that decay rates are fundamental constants of nature, just as the masses of the radioisotopes themselves are. Recently, the belief that decay rates are fundamental constants has been called into question following the observation of various reported anomalies in decay rates, such as apparent periodic variations. The purpose of this bibliography is to collect in one place the relevant literature on both sides of this issue in the expectation that doing so will deepen our understanding of the available data.

1. Introduction

In recent years numerous experiments have presented evidence questioning whether decay rates of radioactive nuclei, or equivalently their half-lives, are fundamental constants of nature, as is generally believed. As examples, data from an experiment extending between 1982–1986 at Brookhaven National Laboratory (BNL) by Alburger et al. [1] on the half-life of $^{32}$Si exhibited clear annual periodicities, which the authors could not account for in terms of temperature variations or other conventional environmental influences [2]. Similarly, data taken between 1983 and 1998 at the Physikalisch-Technische Bundesanstalt (PTB) in Germany [3] exhibited annual variations similar to those observed at BNL. Some have argued that such fluctuations are due to experimental influences and improper uncertainty calculations [1].

A possible interpretation of these data is that they may be attributable to the annually varying flux of solar neutrinos, or from a contribution of axionic dark matter,

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which were perturbing nuclear decay rates. Support for this conjecture comes from a report by Davis [5] of an increase in the number of solar neutrinos detected in his Homestake solar neutrino experiment associated with a solar storm on 4 June 1991. The subsequent observation of a precipitous drop in the decay rate of $^{54}$Mn associated with a significant solar storm on 13 December 2006 [6], further supports the suggestion that at least some nuclear decay rates could be influenced by changes in the local flux of neutrinos, or other particles such as axionic dark matter coupling to baryons.

Notwithstanding the implications of the preceding discussion, it has also become clear that not all nuclei exhibit fluctuations in response to the same perturbations. This follows, for example, from the discussion in Ref. [7] of data acquired during the GW170817 neutron star inspiral: of the three isotopes studied in the experiment described there, $^{44}$Ti and $^{60}$Co exhibited an effect similar to that observed in Ref. [8] for $^{32}$Si and $^{36}$Cl, but $^{137}$Cs did not. Since at present there is no theory to account for how some nuclear decay rates could be influenced by a flux of neutrinos or perhaps other solar influences, it is not surprising that some nuclei may be more responsive to an external influence than others.

A recent paper provides additional support for a theory in which the observed periodic variations in radioactive decays could arise from dark matter coupling to baryonic number [9]. This reference explores the similarity between signals seen in neutrino detectors and gravitational antennas during SN1987A, and a similar signal during the GW178017 neutron star inspiral in an experiment monitoring the half-life of $^{32}$Si. It is demonstrated that the similarity of these signals is attributed to the influence of a gravity wave on a component of dark matter that couples to baryons. Since this component could directly influence the decay rates of unstable nuclei, this picture provides a natural mechanism to account for gravitationally-induced variations in radioactive decays.

Although there is at present no theory to explain how different nuclei might respond differently to changes in the local flux of neutrinos, axions, or other particles in the interstellar medium, one possible mechanism relies on the known sensitivity of nuclear decay rates to the available phase space for their daughter particles.

One approach that is being explored is to assume that a component of the ambient stellar medium influences some nuclear decay rates by modifying the phase space available for their daughter particles. This “medium” approach has two attractive features: First, it could explain the surprising observation [10] that the annual fluctuations $\Delta \Gamma_i/\Gamma_i$ in many decay rates $\Gamma_i$ are approximately the same, even though the magnitudes of the $\Gamma_i$ vary over 9 orders of magnitude. Secondly, the neutrino kinematics in the medium picture allow for the effective observed neutrino mass $(m^2_\nu)_{\text{eff}}$ to be negative, in agreement with observation, even though the intrinsic neutrino mass $(m^2_\nu)$ is positive [10].

In summary, there is at present a growing literature from well-done experiments suggesting that some nuclear decay rates may exhibit fluctuations arising from external influences. There is also an extensive literature from equally well-done experiments
where such fluctuations were sought but not found. Since at present, there is no quantitative theory to account for the observed fluctuations, it is difficult to draw any firm conclusions about the origins of the observed fluctuations. It is clear that much remains to be learned about potential external influences on radioactive decay rates, from both experimental and theoretical standpoints.

As a means to organize the literature we have noted for each reference whether they have reported variations (V) or no variations (NV) from the expected exponential decay law. We have separately considered α-decays, β-decays, electron capture-decays and γ-decays, where appropriate. The present situation is further complicated by disagreements in the published values of the half-lives of various radionuclides, some of which we present in an appendix to the main review. Although these disagreements can be reconciled using various algorithms, the question remains as to whether they could arise from the same mechanisms which constitute the body of this review. Given the possible connection of this literature to the central focus of the present review, we have also included a selection of appropriate references, which are denoted by “D”.

In the bibliography, we have organized the literature alphabetically to allow for easy access to specific papers. Additionally, in Table 1 we have cross-referenced the experiments in a manner that allows the interested reader to focus on common features of specific experiments, such as which isotopes were studied and which detectors were employed.

By organizing the literature in this way, we hope to aid researchers in resolving the many issues that remain in this field. Any attempt to explain the anomalies by experimental or environmental effects will need to reproduce the observations in a convincing way. Similarly, any theory requiring beyond the Standard Model physics to explain the anomalies needs to be consistent with all other observations and be testable in other types of experiments.

Finally, we recognize that despite our many efforts to compile a useful reference which is as complete as possible, we may have inadvertently omitted some references which should have been included. Since we plan to update this bibliography as needed, we invite suggestions for additional references to be included in future editions. These suggestions should be sent to the corresponding author.

Acknowledgments

This article is based upon work sponsored by the Defense Advanced Research Projects Agency (DARPA). Any opinions, findings, conclusions or recommendations expressed are those of the authors and do not necessarily reflect the views of DARPA, the U.S. Air Force, the U.S. Department of Defense, or the U.S. Government. We wish to thank Bianca Caminada, Emily Kincaid, Claire Landgraf, Connor Mohs, Connor Petway, and Ethan Zweig for their help in compiling this bibliography.
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Anomalies in Radioactive Decay Rates: A Bibliography of Measurements and Theory 5

Table 1: Partial list of time varying and time-independent decay experiments. Institution abbreviations are as listed: GSL: Gran Sasso Laboratory; GSIL: Geological Survey of Israel Laboratory; OPC: Optical Physics Company; MSU: Moscow State University; BNLI: Brookhaven National Laboratory; PTB: Physikalisch-Technische Bundesanstalt; LMSU: The Lomonosov Moscow State University; Baylor: Baylor College of Medicine; U.S.A.F. Academy: U.S. Air Force Academy; KIT: Karlsruhe Institute of Technology; Karpov Institute: Karpov Institute of Physical Chemistry; CRIM: Central Research Institute of Machine, IRES: Institute for Industrial, Radiophysical and Environmental Safety

| Isotope | Decay | Detector Type | Detected | Observations | Institution | Reference |
|---------|-------|---------------|----------|-------------|-------------|-----------|
| H       | β−   | Liquid Scintillator | β−       | 1yr, 12.1yr, 18d, 42d, 12.31yr | Novi Sad, Purdue, USAFA | [12], [63], [28] |
| H       | β+   | Ion Chamber | γ       | No effect | PTB | [29] |
| Na      | β−   | Solid State | γ       | No effect | Berkeley | [52] |
| Na      | β+   | HPGe | γ       | No effect | Novi Sad, Berkeley | [15], [63] |
| Si      | β−   | Scintillation | γ       | GW inspiral, 1yr | Purdue, BNL | [19], [11] |
| Si      | β−   | Ge(Li) | γ       | 1yr | CRIM | [24] |
| Si/Sr/Cr | β−   | Proportional | γ       | No effect | Wadsworth Center | [16], [25] |
| Cl      | β−   | Ion Chamber | γ       | 27d, 1yr | PTB | [12], [44] |
| Cl      | β−   | Proportional | γ       | 1yr, 11.71yr, 2.11yr | Purdue, BNL | [65], [85], [63] |
| Cl      | β−   | Scintillation | γ       | GW inspiral | Purdue | [22] |
| Cl      | β−   | Scintillation | γ       | No effect | PTB | [70] |
| Cl      | β−   | Geiger Muller | β−      | 1yr | Purdue | [65], [25], [58] |
| Cl      | β−   | Geiger Muller | β−      | 1yr | Purdue | [65], [25], [58] |
| K       | β−, EC | Scintillator | γ       | No effect | TBD | [19], [20], [25] |
| Ti      | β−   | EC | γ       | No effect | Zurich, Amsterdam | [20] |
| Ti      | β−   | EC | HPGe | γ       | No effect | Berkeley | [20] |
| Mn      | β−   | EC | Scintillation | γ       | Solar flare | Purdue | [20] |
| Mn      | β−   | EC | Scintillation | γ       | 1yr | Purdue, Baylor | [65], [85] |
| Mn      | β+   | EC | Scintillation | γ       | 1yr | Purdue | [20] |
| Fe      | β−   | EC | Scintillation | γ       | No effect | PTB | [20] |
| Co      | β+   | Na(Tl) | γ       | No effect | Zurich, Amsterdam | [20], [41] |
| Co      | β+   | Na(Tl) | γ       | 1d, 27d, 1yr | CRIM | [23], [24] |
| Co      | β+   | Scintillation | γ       | 1d, 12.11yr, 10d, 20d, 27d | CRIM | [23], [24] |
| Co      | β+   | HPGe | γ       | 1yr | IMS | [20] |
| Co      | β+   | Ge(Li) | γ       | No effect | BNL | [23] |
| Co      | β+   | Geiger Muller | β−      | 1yr | LMSU, Purdue, USAFA | [103], [104], [28] |
| Re      | β−   | Geiger Muller | β−      | 1yr, 11.71yr, 10yr | LMSU, Purdue, USAFA | [103], [104], [54], [84] |
| Zn      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ga      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Rh      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ru      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Kr      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Sr      | β−   | Geiger Muller | β−      | 1yr, 11.71yr, 10yr | LMSU, Purdue, USAFA | [103], [104], [54], [84] |
| Sr      | β−   | Scintillation | γ       | 10yr | PTB | [20] |
| Sr      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Tc      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Mo      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ru      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ag      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ag      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ag      | β−   | HPGe | γ       | No effect | Berkeley | [20] |
| Cd      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| In      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Sn      | β−   | HPGe | γ       | No effect | Berkeley | [20] |
| Tl      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Th      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Pa      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Rn      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ba      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ba      | β−   | HPGe | γ       | No effect | Berkeley | [20] |
| Cs      | β−   | Scintillation | γ       | 1d, 12.11yr | CRIM, Purdue, OSU | [20], [63], [76] |
| Cs      | β−   | Na(Tl) | γ       | No effect | Zurich | [20] |
| Cs      | β−   | Geiger Muller | β−      | No effect | PTB | [20] |
| Cs      | β−   | Geiger Muller | β−      | Solar Eclipse | Greenland | [20] |
| Cs      | β−   | HPGe | γ       | No effect | TBD, IMS | [21], [16] |
| Cs      | β−   | Ion Chamber | γ       | 27d | PTB | [20] |
| Cs      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Cs      | β−   | Ion Chamber | γ       | No effect | PTB | [20] |
| Ec      | β−   | Solid State (Ge) | γ       | 1yr | Purdue, PTB, USAFA | [20], [63], [131], [76] |
| Ec      | β−   | HPGe | γ       | 1yr | IMS | [20] |

Continued on next page
| Isotope | Decay | Detector Type | Detected | Observations | Institution | Reference |
|---------|-------|---------------|----------|--------------|-------------|-----------|
| 152Eu  | EC, β− | Ion Chamber   | γ        | 1yr          | PTB, USAFA  | [68], [76] |
| 152Eu  | β−     | Ion Chamber   | γ        | No effect    | PTB         | [126], [130] |
| 153Eu  | β−     | Ion Chamber   | γ        | 1yr          | Purdue      | [68], [88] |
| 154Eu  | β−     | Ion Chamber   | γ        | No effect    | PTB         | [127], [128], [130] |
| 157Eu  | β−     | Ion Chamber   | γ        | No effect    | PTB         | [127] |
| 190Re  | β−     | Ion Chamber   | γ        | No effect    | PTB         | [127] |
| 198Au  | β−     | HPGe          | γ        | Neutrino flux| MSU, Purdue | [74], [92], [135] |
| 204Ti  | β−     | Geiger Muller | γ        | No effect    | PTB         | [127] |
| 222Rn  | α, β−  | Scintillation | γ        | 1yr, 11.71yr, 2.11yr, 1d | GSIL, PTB  | [122], [143], [84] |
| 222Rn  | α, β−  | NaI Crystal   | γ        | 1d, 27d, 1yr | GSIL        | [122], [143] |
| 224Ra  | α, β−  | Ion Chamber   | γ        | No effect    | PTB         | [127] |
| 226Ra  | α, β−  | Ion Chamber   | γ        | No effect    | Purdue, BNL, | [63], [65], [88], [127], [128], [133] |
| 229Th  | α      | NaI Crystal   | γ        | 1d          | GSIL        | [128] |
| 233U   | β−     | SpaceCraft    | α        | Seasonal     | Wabash, Purdue | [73] |
| 235U   | β−     | Solid State   | α        | 1d, 1yr, 13.51yr | MSU, Purdue | [75], [85], [88] |
| 239Pu  | β−     | Geiger Muller | γ        | No effect    | LMSU        | [80] |
Key to Paper Categories

| General Categories | Qualifiers       |
|--------------------|-----------------|
| V                  | E Experimental  |
| NV                 | P Phenomenological |
| A                  | T Theoretical   |
| B                  | L Laboratory   |
| EC                 | R Review       |
| G                  | S Solar Influence |
| D                  |                |

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