Abstract

Experiments showing a seasonal variation of the nuclear decay rates of a number of different nuclei, and decay anomalies apparently related to solar flares and solar rotation, have suggested that the Sun may somehow be influencing nuclear decay processes. Recently, Cooper searched for such an effect in $^{238}$Pu nuclei contained in the radioisotope thermoelectric generators (RTGs) on board the Cassini spacecraft. In this paper we modify and extend Cooper’s analysis to obtain constraints on anomalous decays of $^{238}$Pu over a wider range of models, but these limits cannot be applied to other nuclei if the anomaly is composition-dependent. We also show that it may require very high sensitivity for terrestrial experiments to discriminate among some models if such a decay anomaly exists, motivating the consideration of future spacecraft experiments which would require less precision.

Keywords: Radioactive decay, Sun, Deep-space probes, New forces, Neutrinos

1. Introduction

In a recent paper [1], early data from a sample of $^{137}$Cs on board the MESSENGER spacecraft enroute to Mercury were analyzed to set limits on a possible solar influence on nuclear decay rates. This work was motivated by the suggestion put forward in a recent series of papers which cite evidence for a drop in the count rate of $^{54}$Mn during a solar flare [2], for a correlation between decay rates of various isotopes and Earth-Sun distance [3, 4, 5, 6, 7, 8, 9, 10, 11] and for periodicities in decay-rate data associated with solar rotation [12, 13]. Although the suggestion of a solar influence on nuclear decay rates has been challenged by the apparent absence of decay anomalies in some isotopes that have been studied [15, 16, 17], and by a recent reactor experiment [18], there is no a priori reason to assume that all isotopes should be equally sensitive to a putative solar influence, or that the antineutrinos produced in reactors would be the dominant agents through which a solar influence would be exerted. As we have noted elsewhere [4,19,20], the very same properties of decaying nuclides that are responsible for the broad range of observed half-lives (e.g., nuclear and atomic wave-functions, $Q$-values, selection rules) would likely render nuclides sensitive in different degrees to a putative solar influence.

The suggestion that the Sun is responsible for variations in decay rates can be tested directly by studying the decay rates of appropriate nuclides located on spacecraft traveling through the solar system. While such a specifically-designed mission has yet to be carried out, a number of spacecraft have been launched to date carrying radioactive nuclides that can be used to constrain decay anomalies. As mentioned above, Ref. [1] develops a general formalism for constraining decay anomalies for nuclides placed on board spacecraft, such as the $^{137}$Cs source on board MESSENGER. Additionally, as noted by Cooper [16], the radioactive nuclides (e.g., $^{238}$Pu) used to generate electrical power on spacecraft like Cassini via radioisotope thermoelectric generators (RTGs) can also be used to set limits on decay anomalies. The goal
of this paper is to apply the general formalism developed in Ref. [11] to spacecraft-borne RTGs.

The outline of our paper is as follows: In Sec. 2 we present the general formalism that develops the phenomenology characterizing a wide range of models of solar-induced decay anomalies, and show why experiments on board spacecraft may be crucial in studying them. In Sec. 3 we describe how this phenomenology can be applied to obtain limits from spacecraft-borne RTGs. In Sec. 4 we apply our formalism to the Cassini mission, modifying and extending Cooper’s work [16] to a wider class of models. We conclude in Sec. 5 with a summary and discussion of our results.

2. General Formalism

We begin by briefly reviewing the formalism developed in Refs. [1][13] to describe anomalous radioactive decays. If \( N(t) \) is the number of unstable nuclei in a sample located at position \( \vec{r} \), then we will assume that the total activity of the sample is

\[
- \frac{dN(t)}{dt} = \lambda(t)N(t) = [\lambda_0 + \lambda_1(\vec{r}, t)]N(t),
\]

where \( \lambda_0 \) represents the intrinsic contribution to the decay rate of the unstable nuclei, along with a possible time-independent background arising from new interactions. Here \( \lambda_1(\vec{r}, t) \ll \lambda_0 \) characterizes the anomalous position- and time-dependent contribution to the decay rate, assumed, in this case, to arise from the Sun.

As noted above, there is evidence using terrestrial radioactive samples suggesting that decay rates are correlated with sample-Sun separation. To study this effect, we will assume a specific phenomenological form for \( \lambda_1(\vec{r}, t) \) given by [11]

\[
\lambda_1(\vec{r}, t) = \lambda_0 \xi^{(n)} \left( \frac{R}{r(t)} \right)^n,
\]

where \( n = 1, 2, 3, \ldots, r = |\vec{r}| \) is now the sample-Sun separation distance, \( R = 1 \text{ AU} = 1.495979 \times 10^8\text{ km} \), and \( \xi^{(n)} \) is a composition-dependent dimensionless parameter characterizing the “strength” of the decay anomaly for a specific nucleus. The form of Eq. (2) is designed to encompass a broad range of theories. If the decay anomalies are caused by a flux of neutrinos from the Sun or by an inverse-square law field, then one expects \( n = 2 \). On the other hand, radioactive decay processes might be affected by one of the many proposed new long-range inverse-power-law interactions. In this case, the potential energy between point particles of mass \( m_1 \) and \( m_2 \) separated by distance \( r \) may be written in the general form [21]

\[
V_n(r) = -\alpha_n \left( \frac{Gm_1m_2}{r} \right) r^{-n}.
\]

where \( \alpha_n \) is a dimensionless constant, \( G \) is the Newtonian gravitation constant, and \( r_0 = 10^{-15}\text{ m} \) is a length scale chosen by convention. For example, \( n = 2 \) can arise from the simultaneous exchange of two massless scalar particles [22], \( n = 3 \) from 2-massless-pseudoscalar exchange [23][24], and \( n = 5 \) from 2-neutrino [25][26] and 2-axion exchange [24].

Because the Earth-Sun variation of \( r \) is small, it is difficult to obtain the dependence on the power \( n \) from a purely terrestrial experiment, which is why the use of spacecraft with widely varying values of \( r \) is important. To show this, we substitute Eq. (2) into Eq. (1), giving

\[
- \frac{dN(t)}{dt} = \lambda(t)N(t) = \lambda_0 \left( 1 + \xi^{(n)} \left( \frac{R}{r(t)} \right)^n \right) N(t).
\]

This form is not very useful since it depends on the instantaneous value of \( N(t) \). Following Ref. [1], we can eliminate this dependence by first integrating Eq. (1), obtaining

\[
N(t) = N_0 \exp\left\{ -\lambda_0 \int_0^t \left[ 1 + \xi^{(n)} \left( \frac{R}{r(t')} \right)^n \right] dt' \right\},
\]

where \( N_0 = N(0) \) and

\[
I^{(n)}(t) = \int_0^t dt' \left[ \frac{R}{r(t')} \right]^n.
\]

Then differentiating Eq. (5) gives

\[
\dot{N}(t) = \lambda_0 N_0 \exp(-\lambda_0 t) \left( 1 + \xi^{(n)} \left( \frac{R_0}{r(t)} \right)^n - \lambda_0 I^{(n)}(t) \right),
\]

where \( \dot{N}(t) \equiv dN(t)/dt \) and assuming \( \xi^{(n)} I^{(n)}(t) \ll 1 \). For our application, we will set \( t = 0 \) to be the launch time of the spacecraft, in which case \( r(0) = R \). Then, using \( I^{(n)}(0) = 0 \), Eq. (7) yields

\[
\dot{N}(0) = \lambda_0 N_0 \left[ 1 + \xi^{(n)} \right].
\]

For practical purposes, it is useful to express Eq. (7) in terms of directly measurable quantities. If we define \( \lambda \equiv \lambda_0[1 + \xi^{(n)}] \) to be the decay rate observed on Earth when \( r = R \), then \( \lambda_0 \equiv [\lambda(1 + \xi^{(n)}) + \lambda(\xi^{(n)})^2]. \) Substituting this into Eq. (7) and retaining only terms of leading order in \( \xi^{(n)} \), we find after using Eq. (8) that [11]

\[
\dot{N}(t) = N(0)e^{-\lambda t} \left[ 1 + \xi^{(n)} B^{(n)}(t) \right],
\]

where

\[
B^{(n)}(t) = \int_0^t dt' \left[ \frac{R}{r(t')} \right]^n.
\]
Combining Eqs. (9) and (13), we find that the activity

\[ B^{(a)}(t) = \left( \frac{R}{r(t)} \right)^n - 1 - \lambda \left[ I^{(a)}(t) - I \right]. \]  

(10)

For later purposes, we note from Eq. (10) that \( B^{(a)}(0) = 0 \). The terms in brackets in Eq. (10) represent the anomalous contributions to \( \dot{N}(t) \) arising from the circumstance that at some \( t \) the sample is at \( r(t) \), rather than at \( R \). The second term in square brackets represents an additional cumulative contribution to \( \dot{N}(t) \) from the variation of \( r(t) \) from \( t = 0 \) to \( t \), and this is generally nonzero even when \( r(t) = R \) (see below).

We will now demonstrate why spacecraft missions

\[ \dot{N}_B(t) = \dot{N}_B(0) \sin \left( \frac{2\pi}{T} \right) + O(\epsilon_B^2), \]  

(11)

where \( \dot{N}_B \approx R \) is the mean Earth-Sun separation, \( T = 1 \) year is the orbital period, and \( t = 0 \) when the Earth is at \( r = R \). Substituting Eq. (11) into Eq. (6) and integrating, while keeping only terms of \( O(\epsilon_B^2) \), we find

\[ I^{(a)}(t) \approx I - \frac{\dot{n}_B}{T} \int \left[ 1 - \cos \left( \frac{2\pi t}{T} \right) \right], \]  

(12)

so \( B^{(a)}(t) \) given by Eq. (10) becomes, after neglecting terms of \( O(\epsilon_B^2) \),

\[ B^{(a)}(t) \approx -\dot{n}_B \left\{ \sin \left( \frac{2\pi}{T} \right) - \frac{\lambda T}{2\pi} \left[ 1 - \cos \left( \frac{2\pi t}{T} \right) \right] \right\}. \]  

(13)

Combining Eqs. (9) and (13), we find that the activity of a sample on Earth is given by

\[ \dot{N}_B(t) \approx \dot{N}_B(0) e^{-\lambda t} \left\{ 1 - n \dot{e}^{(a)} I_B \left[ \sin \left( \frac{2\pi t}{T} \right) \right] \right\} - \frac{\lambda T}{2\pi} \left[ 1 - \cos \left( \frac{2\pi t}{T} \right) \right] \right\}. \]  

(14)

Since \( n \) and \( \dot{e}^{(a)} \) appear together only in the combination \( n \dot{e}^{(a)} \) in Eq. (14), it is not possible to distinguish between theories with different values of \( n \) using terrestrial decay experiments unless one has sufficient sensitivity to detect effects of \( O(\epsilon_B^2) \approx 3 \times 10^{-4} \). On the other hand, by placing radioactive samples on board spacecraft, a decay anomaly can be probed over a wide range of \( r(t) \), allowing one to discriminate more easily between the various powers of \( n \) given in Eq. (9).

3. Application to RTGs

The thermoelectric generators on board spacecraft use the Seebeck effect to convert heat from a hot reservoir into electrical power, while waste heat is exhausted into a cold reservoir. In a simple model [27], the total electrical power output can be written as

\[ P_{el}(t) = I \Delta V_{term}, \]  

(15)

where \( I \) is the current, and the terminal voltage across the generator is given by

\[ \Delta V_{term} = \alpha_{a,p}(T_H - T_C) - IR_{int}. \]  

(16)

Here \( \alpha_{a,p} \) is the differential Seebeck coefficient for the \( n \)- and \( p \)-doped semiconductor generator leg, \( T_H \) and \( T_C \) are the temperatures of the hot and cold heat reservoirs, and \( R_{int} \) is the internal resistance of the generator. The efficiency of a thermoelectric generator is usually expressed as

\[ \eta_{TG} = \frac{P_{el}}{\dot{Q}_H}, \]  

(17)

where \( \dot{Q}_H \) is the thermal power input from the hot reservoir.

An RTG is a thermolectric generator that uses a radioactive material as its hot temperature reservoir. RTGs have been placed on board spacecraft since the early 1960s [27][28], and are typically used on probes traveling outward in the solar system where solar panels do not provide sufficient power. These missions include Pioneer 10 and 11, Voyager 1 and 2, Galileo, Ulysses, Cassini, and New Horizons. In addition, RTGs were used to power instruments on the two Viking landers on Mars, and instruments on the Moon placed by Apollo astronauts.

The thermal power \( P_{th}(t) \) generated by the radioactive heat source of an RTG is directly proportional to \( \dot{N}(t) \), the activity of the radioactive material used. Therefore, we can use Eq. (9) to relate the thermal power generated at time \( t \) to the thermal power produced at launch \( t = 0 \):

\[ P_{th}(t) = P_{th}(0) e^{-\lambda t} \left[ 1 + \xi^{(a)} B^{(a)}(t) \right]. \]  

(18)

Unfortunately for our purposes, this thermal power is not directly observed. Instead, the electrical power \( P_{el}(t) \) given by Eq. (15) is measured. To relate \( P_{el}(t) \) to \( P_{th}(t) \), we follow Cooper [16] and introduce the dimensionless efficiency function \( \epsilon(t) \) defined by

\[ P_{el}(t) \equiv \epsilon(t) P_{th}(t), \]  

(19)

where

\[ \epsilon(t) = \eta_{TG}(t) \eta_{rad}(t), \]  

(20)
and
\[ \eta_{\text{rad}} \equiv \frac{\dot{Q}_H}{P_{\text{el}}} \]  
(21)
is the fraction of the total radioactive thermal power that flows into the generator. Eq. (18) can then be rewritten as
\[ P_{\text{el}}(t) = P_{\text{el}}(0) e(t) e^{-\lambda t} \left[ 1 + \xi^{(n)} B^{(n)}(t) \right], \]  
(22a)

\[ = P_{\text{el}}(0) e(t) 2^{-t/t_{1/2}} \left[ 1 + \xi^{(n)} B^{(n)}(t) \right], \]  
(22b)
where \( t_{1/2} = (\ln 2)/\lambda \) is the half-life of the nuclide. We note that \( e(t) \) is time dependent since RTG efficiency generally decreases with time.

For our problem, \( e(t) \) must be determined in a manner that is not influenced by the presence of a decay anomaly, and one option is to use a computer model. However, the model commonly used to describe RTG performance (DEGRA [30]) assumes the usual exponential decay of the radionuclide, preventing its use in testing the exponential decay hypothesis [16]. The alternative suggested by Cooper [16] is to use an empirical approach that capitalizes on the fact that there may be points along a spacecraft’s trajectory where anomalous decay effects make no contribution, which from Eq. (22), occurs whenever \( B^{(n)}(t) = 0 \).

In his analysis of Cassini power data, Cooper utilized five points at times where \( r(t) = R \), but from Eq. (10) we see that
\[ B^{(n)}(r = R) = -\lambda \left[ T^{(n)}(t) - 1 \right], \]  
(23)
which does not generally vanish for \( t > 0 \), though in the specific case of Cassini studied by Cooper, this is a reasonable approximation. If we define the decay-normalized power as
\[ \mathcal{P}(t) \equiv 2^{t/t_{1/2}} P_{\text{el}}(t)/P_{\text{el}}(0) = e^{\lambda t} P_{\text{el}}(t)/P_{\text{el}}(0), \]  
(24)
and use only power data where \( B^{(n)}(t) = 0 \), then we can solve Eq. (22) for \( e(t) \) in terms of known quantities,
\[ e(t) = \mathcal{P}(t; B^{(n)} = 0), \]  
(25)
and fit the results to an empirical function as we will demonstrate in the next section.

This analysis indicates that decay anomalies can, in principle, be detected using the electrical power output as a proxy for the (time-dependent) energy release from nuclear decays in spacecraft RTGs. All that is required is: (1) a spacecraft trajectory with a significant variation of \( r(t) \) (preferably including \( r(t) \ll R \)), (2) accurate measurements of the spacecraft’s position and electrical power production, and (3) a good model of the RTG efficiency function \( e(t) \) that does not assume the radioactive decay law. If a computer model for the efficiency is unavailable, an empirical approach can be used, provided there are a sufficient number of points where \( B(t) = 0 \). The original Solar Probe Plus mission, which would have used a spacecraft powered by RTGs while using a Jupiter gravity assist maneuver to place it into solar polar orbit, would have been ideal for our purposes [31]. However, this planned mission has been changed to avoid the use of RTGs. Of the interplanetary missions that have used RTGs, only Cassini and Galileo actually crossed the 1-AU orbit radius after launch, allowing the empirical approach. Since the Cassini mission crossed the most times, it provides the most complete data to model the RTG efficiency empirically and so will be used in this paper.

We note in passing that accurate modeling of RTGs has also been important in understanding the Pioneer anomaly, the small anomalous acceleration of both Pioneer 10 and 11 spacecraft [32]. In order to explain the observed temporal decay of this acceleration, the changes in thermal recoil forces on these spacecraft due to the degradation of the RTGs need to be accurately modeled [33].

4. Application to Cassini RTG Data

Launched in 1997, the Cassini spacecraft made several gravity-assisted flybys of Venus, Earth, and Jupiter before entering the Saturn system in 2004. In principle, this nearly 7-year-journey provides both a sufficiently long duration and a substantial variation in \( r(t) \) to render Cassini ideal for a test of solar-influenced radioactive decays. However, following Cooper [16], we will only use the first two years of data, when \( 0.6732 \text{ AU} \leq r \leq 1.6215 \text{ AU} \), because only within this range can we determine with some confidence the efficiency function \( e(t) \). For \( t > 2 \text{ years} \), there are no longer any times where \( B^{(n)}(t) = 0 \) which can be used to perform the empirical fit to determine \( e(t) \).

The Cassini spacecraft uses three General Purpose Heat Source Radioisotope Thermal Generators (GPHS-RTGs), each producing nearly 300 W of electrical power from 572 thermoelectric “unicouples.” A GPHS generates approximately 4410 W of thermal power at the beginning of life from PuO\(_2\) fuel pellets enriched to about 80\% \( ^{238}\text{Pu} \), corresponding to about 8.1 kg of \( ^{238}\text{Pu} \) per generator [33]. The pellets were formed from PuO\(_2\) powder obtained from Russia, where the plutonium was created by irradiating \( ^{237}\text{Np} \) in a high-flux reactor to form \( ^{238}\text{Np} \) which has a half-life of 2.4 days [29]. A \( ^{238}\text{Np} \) nucleus decays to \( ^{238}\text{Pu} \) via a \( \beta^- \)-decay.
For the rest of this analysis, we will assume that all of the thermal heat production of a GPHS results from \(^{238}\text{Pu}\), which has a half-life \(t_{1/2} = 87.7\) years. (The most likely nuclide present would be \(^{238}\text{Pu}\), whose half-life is \(2.41 \times 10^{10}\) yr, and hence decays too slowly to contribute significantly to the energy production in an RTG.)

Our analysis begins with Cassini’s trajectory and RTG current \(I(t)\) data provided by the Jet Propulsion Laboratory. Since the current is monitored separately for each RTG, each can provide a separate determination of the material-dependent parameter \(\xi_n\) for \(^{238}\text{Pu}\), and together the RTGs can be used to assess the validity of the empirical efficiency function \(\epsilon_{\text{emp}}(t)\). A total of 157,465 current measurements (in increments of 0.03959 A) were taken over the 2-year period at irregular intervals, and a small number of obviously spurious points were removed before our analysis began. The Cassini power system is regulated with a variable shunt radiator to maintain a constant terminal voltage \(\Delta V_{\text{term}} = 30.0 \pm 0.2\) V across each RTG to maximize power production \(155\), and hence the RTG electrical power was obtained from the current measurements using Eq. (15). Since the variable shunt regulator is located “downstream” from the RTG, its operation does not affect our ability to determine the RTG’s power output as a function of time. The results are shown in Fig. 1 with digitization of the current measurements clearly evident. The power decreases more rapidly than expected from the radioactivity exponential decay law for \(^{238}\text{Pu}\) due to unicouple degradation among other factors.

Using the Cassini trajectory data, \(B^n(t)\) for \(n = 1–5\) was computed using Eq. (10) for \(0 \leq t \leq 2\) years, and is plotted in Fig. 2. We note that \(B^n(t)\) increases with \(n\), so the constraints on \(\xi_n\) become more stringent as \(n\) increases. From Eq. (10), we see that the largest values of \(B^n(t)\), which lead to the largest decay anomalies, occur when \(r(t)\) is smallest. For Cassini, this occurs at its closest approach to the Sun, \(r = 0.6732\) AU at \(t = 0.45\) yr, with smaller peaks at \(t = 1.7\) yr.

Using the data from each of the three RTGs for the first two years, we calculated the decay-normalized power \(P(t)\) using Eq. (24). For the 5 data points where \(B^n(0) = 0\), we then determined \(\epsilon(t)\) following Eq. (25) by plotting for each RTG \(\epsilon(t) = P(t; B = 0)\) versus \(t\), and then fitting the results to an empirical function similar to that suggested by Cooper \[16\].

\[
\epsilon_{\text{emp}}(t) = 2^{-t/T_{\text{eff}}} \left(1 + at + bt^2 + ct^3\right),
\] (26)

where \(T_{\text{eff}}\), \(a\), \(b\), and \(c\) are constants. [Note that our procedure differs from Cooper who only used \(\epsilon_{\text{emp}}(t) = 2^{-t/T_{\text{eff}}}\) for the points where \(r(t) = R\). The third-order polynomial portion of Eq. (25) was introduced later and fit using all of the trajectory data \(0 \leq t \leq 2\) yr.] The result for \(n = 2\) is shown in Fig. 3. The results for the other values of \(n\) are virtually identical. We see that there is some relative variation among the three RTGs, and we use this variation to estimate the relative uncertainty in the empirical efficiency function to be \(\delta\epsilon_{\text{emp}}/\epsilon_{\text{emp}} \lesssim 0.5\%\).

We can assess the validity of our empirical approach...
for determining $\epsilon(t)$ by examining the quantity

$$\Delta(t) \equiv \left[ \frac{P(t)}{\epsilon_{\text{emp}}(t)} - 1 \right], \quad (27)$$

which would vanish if $\epsilon_{\text{emp}}(t)$ gave a perfect characterization of $P(t)$. In Fig. 4, $\Delta$ is plotted versus $t$ and $r$. Using the combined data from all three RTGs, we find

$$|\Delta(t)| \lesssim 0.005, \quad (28)$$

with no significant systematic dependence of $\Delta$ on $t$ or $r$ other than the effects due to the digitization of the power seen in Fig. 1. Thus, $\epsilon_{\text{emp}}(t)$ gives a good characterization of the decay-normalized power of the RTGs to the level of 0.5%. Systematic effects due to solar heating of the RTGs, which would depend on $1/r^2$, are not evident. The semiconductor legs of the unicouples generating the power via the temperature difference $T_H - T_C$ are only 20.3 mm long [34]. Only a differential heating over this distance scale would produce a change in the RTG electrical power production, which is not seen.

Now that the efficiency function $\epsilon(t) = \epsilon_{\text{emp}}(t)$ has been determined, all quantities in Eq. (22) are known except for $\xi_{\text{Pu}}^{(n)}$. Inserting Eq. (24) into Eq. (22) and setting $\epsilon(t) = \epsilon_{\text{emp}}(t)$, we can solve for $\xi_{\text{Pu}}^{(n)}$ to obtain

$$\xi_{\text{Pu}}^{(n)} = \frac{\Delta(t)}{B^{(n)}(t)}, \quad (29)$$

where we have used Eq. (27). Inserting the numerical limit on $\Delta(t)$ given by Eq. (28) into Eq. (29), we find

$$|\xi_{\text{Pu}}^{(n)}| \lesssim \frac{0.005}{|B^{(n)}(t)|}. \quad (30)$$
at time to take into account the fact that the sample’s activity our approach is not a simple power law since one needs The anomaly in the power production of the RTGs in our more fundamental formula for \( \lambda \) given by Eq. (2).

The sensitivity models, but also provide improved tests of the missions could not only be used to refine RTG perfor-

ments will require unusually high sensitivity to discrim-

inating effects should be characterized by the same power \( n \) and all experiments using the same nuclide should yield the same value of \( \xi^{(n)} \). Work is currently under way to apply Eq. (2) to the results of terrestrial experiments, as described in Sec. 2. The only previously reported result is \( \xi^{(2)}_{\text{Cs}} = (2.8 \pm 8.1) \times 10^{-3} \) for the \(^{137}\)Cs sample aboard the Messenger spacecraft [11].

We have also shown that if an inverse-power-law form given by Eq. (2) exists, terrestrial decay experiments will require unusually high sensitivity to discrimi-

nating \( \xi^{(n)} \) from \( n \) since only the combination \( n \xi^{(n)} \) appears to first order in the orbital eccentricity. Thus, experiments conducted on board spacecraft may be needed to distinguish among the various powers of \( n \).

While we and Cooper [16] have shown that spacecraft-

borne RTGs can be used, the isotopes used for power generation are very limited, and hence dedicated experi-

ments using nuclides that have demonstrated a decay process so one cannot, without additional assump-

tions, use the limits on \( \xi^{(n)} \) for \(^{238}\)Pu to constrain anomalous decays of other nuclides or to refute the obser-

vations of previous experiments. The Cassini RTGs are powered exclusively by alpha-decays due to the extrem-

ely long half-lives of the uranium daughters, particularly \(^{234}\)U (\( t_{1/2} = 246,000 \) yr) which is the first daugh-

ter of \(^{238}\)Pu. The absence of a decay anomaly for \(^{238}\)Pu contrasts with the other isotopes in which an anomaly has potentially been observed [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14], that are beta-decays or (like \(^{226}\)Ra) where one actually measures a significant beta-decay component of daughter products [16]. For example, Parkhov [8], found time-dependent fluctuations in \(^{90}\)Sr, \(^{90}\)Y, and \(^{56}\)Co, all of which are beta decays, but not in \(^{238}\)Pu which, like \(^{238}\)Pu studied in this paper, is an alpha decay. Each radioactive nuclide needs to be examined separately for anomalous decay processes, and \( \xi^{(n)} \) determined for each. If Eq. (2) is correct, all anomalous ef-

dicts should be characterized by the same power \( n \) and

all experiments using the same nuclide should yield the same value of \( \xi^{(n)} \).

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borne RTGs can be used, the isotopes used for power generation are very limited, and hence dedicated experi-

ments using nuclides that have demonstrated a decay anomaly in terrestrial experiments should be used.

Since RTGs will continue to be a power source on board spacecraft, improved instrumentation on future missions could not only be used to refine RTG perfor-

mance models, but also provide improved tests of the radioactivity exponential decay law. The two major fac-

tors limiting constraints on decay anomalies using the Cassini RTGs are the uncertainties of the empirical ef-

Table 1: The constraints on \( \xi^{(n)}_{\text{Pu}} \) for \(^{238}\)Pu obtained from Eq. (30) when \( |B^{(n)}(t)| = B^{(n)}_{\text{max}} \).

| \( n \) | \( B^{(n)}_{\text{max}} \) | \( \xi^{(n)}_{\text{Pu}} \) |
|---|---|---|
| 1 | 0.48 | < 1.0 \times 10^{-2} |
| 2 | 1.19 | < 4.2 \times 10^{-3} |
| 3 | 2.25 | < 2.2 \times 10^{-3} |
| 4 | 3.82 | < 1.3 \times 10^{-3} |
| 5 | 6.14 | < 8.1 \times 10^{-4} |

The most stringent limits on \( \xi^{(n)}_{\text{Pu}} \), which are obtained when \( |B^{(n)}(t)| = B^{(n)}_{\text{max}} \), the maximum observed value of \( B^{(n)}(t) \), are presented in Table 1. We see that the tight-
est constraints are obtained for the largest values of \( n \),

which is consistent with our earlier discussion, while a comparatively poor constraint is obtained for \( n = 1 \) since \( B^{(1)}_{\text{max}} \) is relatively small.

5. Discussion

From our analysis of the Cassini RTG power data, we find no evidence of a solar-influenced decay anomaly for \(^{238}\)Pu having the inverse-power-law form given by Eq. (2) for \( n = 1–5 \). Unfortunately, it is difficult to compare our constraints on \( \xi^{(n)}_{\text{Pu}} \) given in Table 1 with the earlier analysis by by Cooper [16], who also found no anomaly. Schematically, Cooper fit the total normalized RTG power production to an empirical efficiency function, and then fit the resulting residuals to two different possible functions characterizing the decay anomaly:

\[
\text{residuals} = \begin{pmatrix}
\alpha \left[ \frac{R}{r} \right]^{2} \\
\beta \left[ \frac{R}{r} \right]
\end{pmatrix}, \tag{31}
\]

where \( R = 1 \) AU. This procedure yielded the 90% confidence level limits

\[
|\alpha| < 0.84 \times 10^{-4}, \tag{32a}
\]

\[
|\beta| < 0.99 \times 10^{-4}. \tag{32b}
\]

However, despite their superficial similarity, Cooper’s formulas given by Eq. (31) are not directly related to our more fundamental formula for \( \lambda_1 \) given by Eq. (2). The anomaly in the power production of the RTGs in our approach is not a simple power law since one needs to take into account the fact that the sample’s activity at time \( t \) actually depends on the sample’s entire history because of its dependence on the function \( I^{(n)}(t) \) given by Eq. (6). Since the two approaches of characterizing the power anomaly are so different, it is difficult to relate

Cooper’s limits on \( \alpha \) and \( \beta \) given by Eq. (32) to our constraints on \( \xi^{(2)}_{\text{Pu}} \) and \( \xi^{(1)}_{\text{Pu}} \), respectively, given in Table 1.

As noted in the Introduction, one expects an anomalous decay mechanism to depend on the nuclei and decay process so one cannot, without additional assumptions, use the limits on \( \xi^{(n)} \) for \(^{238}\)Pu to constrain anomalous decays of other nuclides or to refute the observations of previous experiments. The Cassini RTGs are powered exclusively by alpha-decays due to the extremely long half-lives of the uranium daughters, particularly \(^{234}\)U (\( t_{1/2} = 246,000 \) yr) which is the first daughter of \(^{238}\)Pu. The absence of a decay anomaly for \(^{238}\)Pu contrasts with the other isotopes in which an anomaly has potentially been observed [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14], that are beta-decays or (like \(^{226}\)Ra) where one actually measures a significant beta-decay component of daughter products [16]. For example, Parkhmov [8], found time-dependent fluctuations in \(^{90}\)Sr, \(^{90}\)Y, and \(^{56}\)Co, all of which are beta decays, but not in \(^{238}\)Pu which, like \(^{238}\)Pu studied in this paper, is an alpha decay. Each radioactive nuclide needs to be examined separately for anomalous decay processes, and \( \xi^{(n)} \) determined for each. If Eq. (2) is correct, all anomalous effects should be characterized by the same power \( n \) and all experiments using the same nuclide should yield the same value of \( \xi^{(n)} \). Work is currently under way to apply Eq. (2) to the results of terrestrial experiments, as described in Sec. 2. The only previously reported result is \( \xi^{(2)}_{\text{Cs}} = (2.8 \pm 8.1) \times 10^{-3} \) for the \(^{137}\)Cs sample aboard the Messenger spacecraft [11].


iciency model and the resolution of the electric current (and hence, power) measurements. Additional thermal measurements would also be useful in allowing a more direct determination of the thermal power output of the RTG heat source.

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References

[1] E. Fischbach, K. J. Chen, R. E. Gold, J. O. Goldsten, D. J. Lawrence, R. J. McNutt, E. A. Rhodes, J. H. Jenkins and J. Longaska, Astrophys. Sp. Sci. 337 (2012) 39.
[2] J. H. Jenkins, E. Fischbach, Astropart. Phys. 31 (2009) 407.
[3] J. H. Jenkins, E. Fischbach, J. Buncher, J. Gruenwald, D. E. Krause, J.J. Mattes, Astropart. Phys. 32 (2009) 42.
[4] E. Fischbach, J. Buncher, J. Gruenwald, D. Javorsk II, J. H. Jenkins, R. H. Lee, E. E. Krause, J.J. Mattes, J. Newport, Universe. 78 (1986) 168.
[5] J. Siegert, H. Schrader, U. Schótzig, Appl. Radiat. Isot. 49 (1998) 1397.
[6] E. D. Falkenberg, Aperion 8 (2001), 32.
[7] A. G. Parkhomov, Int. J. Pure Appl. Phys. 1 (2005) 119, arXiv:0710.1591 [arXiv:012.4174]
[8] Y. A. Baurov et al., Mod. Phys. Lett. A 16 (2001) 2089, Phys. At. Nucl. 70 (2007) 1825.
[9] J. K. Ellis, Phys. Med. Biol. 35 (1990) 1079.
[10] S. E. Shnoll et al., Phys. Usp 41 (1998) 1025, Phys. Usp. 43 (2000) 205.
[11] V. Lobashev et al. Phys. Lett. B 460 (1999) 227.
[12] P. A. Sturrock, E. Fischbach, J. H. Jenkins, Solar Phys. 272 (2011) 1.
[13] E. Fischbach, J. H. Jenkins, J. B. Buncher, J. T. Gruenwald, P. A. Sturrock, D. Javorsk II, Proceedings of the Fifth Meeting on CPT and Lorentz Symmetry, ed. by V. Alan Kostelecký, World Scientific, Singapore, 2011, 168.
[14] E. Fischbach, J. H. Jenkins, J. B. Buncher, J. T. Gruenwald, P. A. Sturrock, D. Javorsk II, Proceedings of the Fifth Meeting on CPT and Lorentz Symmetry, ed. by V. Alan Kostelecký, World Scientific, Singapore, 2011, 168.
[15] P. A. Sturrock, E. Fischbach, J. H. Jenkins, Solar Phys. 272 (2011) 1.
[16] E. Fischbach, J. H. Jenkins, J. B. Buncher, J. T. Gruenwald, P. A. Sturrock, D. Javorsk II, Proceedings of the Fifth Meeting on CPT and Lorentz Symmetry, ed. by V. Alan Kostelecký, World Scientific, Singapore, 2011, 168.
[17] E. Fischbach, J. H. Jenkins, J. B. Buncher, J. T. Gruenwald, P. A. Sturrock, D. Javorsk II, Proceedings of the Fifth Meeting on CPT and Lorentz Symmetry, ed. by V. Alan Kostelecký, World Scientific, Singapore, 2011, 168.
[18] R. J. de Meijer, M. Blaauw, F. D. Smit, Applied Radiation Isotopes 69 (2011) 320.
[19] J. H. Jenkins, D. W. Mundy, E. Fischbach, Nucl. Instr. Meth. A 620 (2010) 332.
[20] R. M. Lindstrom, E. Fischbach, J. B. Buncher, J. H. Jenkins, A. K. Hyder, R. L. Wiley, G. Halpert, D. J. Flood, and S. Sabripour, Spacecraft Power Technologies, Imperial College Press, London, 2000.
[21] E. Fischbach, J. H. Jenkins, J. B. Buncher, J. T. Gruenwald, P. A. Sturrock, D. Javorsk II, Proceedings of the Fifth Meeting on CPT and Lorentz Symmetry, ed. by V. Alan Kostelecký, World Scientific, Singapore, 2011, 168.