Final Report

ACCELERATED BETA DECAY

for

DISPOSAL OF FISSION FRAGMENT WASTES

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I. SUMMARY

The ultimate aim of this research is to develop a method to accelerate the radioactive decay rate of high-level fission wastes. To be useful for the disposal of high-level radwaste, the rate acceleration should be large, the physical process should be capable of being applied to large volumes of waste materials, and the method should offer the possibility of low cost in application. The basic physics of a non-nuclear means for doing this is the immediate goal of the research. A research effort along these lines was pursued about twenty years ago with initial cause for hope in its success, but it was ahead of its time and was abandoned. That effort has been renewed with the help of this DOE grant, with extremely promising results.

The fundamental theory of the interaction of intense, low frequency electromagnetic fields with nuclei has been reworked with great care, and the basic physical mechanisms that underlie the coupling of the field to the nucleus have been identified and clarified. There are three such mechanisms, and all are of an inherently strong-field (nonperturbative) nature with no counterparts at ordinary intensities of electromagnetic fields. At the time of the original publication in the 1980s, some criticisms of the proposed physical process were published. With the new understanding of the basic mechanisms, it is now easy to identify the basic defects of the criticisms. All involved methods of calculation that explicitly excluded the fundamental mechanisms for decay rate enhancement.

There were also experiments done in the early 1980s that gave positive but small results, with no simple explanation for the magnitude of rate enhancement observed. That work has also been re-examined. It is now understood why the experiments gave the results they did, and they are now recognized as "proof-of-principle" experiments that are entirely consistent with the theory. That is, the old experiments support the expectation of important (on a practical basis) acceleration of the decay of high-level radioactive waste.

Ongoing work includes the development of explicit numerical predictions for decay rate enhancement, and the design of a new generation of proof-of-principle experiments.

II. INTRODUCTION

An attitude widely held is that nuclear radioactivity is an immutable process. Plainly, radioactivity can be altered by interceding with other nuclear interactions. This is to be expected since radioactivity is a quantum process and, as such, one can find ways of introducing other nuclear interactions to modify the spontaneously occurring nuclear radioactive decay. However, suitable nuclear interactions require the introduction of beams of particles or gamma rays with individual particle energies measured on the scale of excitation energies within the nucleus. That represents a laboratory measure that is unreasonably expensive if the aim is a practical application, such as the disposal of the radioactive waste that is a noxious by-product of the production of energy from nuclear fission.

Non-nuclear means for altering radioactivity have actually been considered for some time, and were demonstrated many years ago [1]. However, those early demonstrations related only to nuclear processes such as internal conversion or electron capture that depended on the participation of atomic electrons. Alteration of atomic-electron structure could affect those types of radioactive processes, but only at very low levels, of the order of one part in a thousand or less.

A different approach was suggested starting in the 1970s, based on the recognition that all high-level radioactive waste exhibits fission-induced "forbidden" beta decays. The word "forbidden" is not absolute; it refers to radioactive processes with half-lives greatly extended because of the violation of quantum selection rules during the nuclear transmutation. Cesium-137 (^{137}Cs) and strontium-90 (^{90}Sr) are leading examples of this type of radioactivity. The proposal was to couple very intense low-frequency electromagnetic fields to the nucleus to supply the necessary quantum units of angular momentum (and/or intrinsic parity) necessary to alter the quantum selection rules and accelerate the radioactive decay [2,3].

More recently, the ability of modern pulsed lasers to be brought to a focus with MeV amounts of energy transferred to individual electrons has pointed to the alteration of radioactivity by this non-nuclear means [4]. Recent experiments have verified this mechanism for radioactivity alteration [5,6].

Laser-induced nuclear processes, while extremely interesting, do not provide the means for satisfying the practical goals set forth in the research reported here. If one is to address the problem of disposal of high-level radioactive wastes, the small focal volumes and very low duty cycles of lasers defeat this application. With a temporal pulse length measured in hundreds of femtoseconds, and cycle rates of less than a kHz, the laser pulse is present for only about one part in 10^{10} of any given interval of time. This, together with focal volumes that are on the order of 10 μm in diameter, prohibit possible application of laser methods to the disposal of the large volumes of high-level waste that exist.

A return to the continuous-wave (CW) methods proposed in the work of the 1970s and 1980s [2,3] has been prompted by several developments.

First, the type of Volkov-solution [7] methods pioneered by the PI many years ago [8] have proven their usefulness for the treatment of intense-field nonperturbative applications like atomic ionization [9,10] and photon-multiphoton pair production [11]. The applicability of Volkov methods to the nuclear problem is much more "pure" than it is in the atomic case, where certain practical limitations exist [12].

Second, the earlier work by the PI on the low-frequency CW acceleration of radioactive decay rates was suspended in the face of some severe criticisms that were raised [13–15]. The DOE-supported research reported on here has permitted a study of the essential physical mechanisms - three in number - that explain the transferral of angular momentum and parity from long-wavelength electromagnetic waves to the very small physical system constituted by the atomic nucleus. It is now recognized that all the critical papers [13,14,?] employed methods of calculation that explicitly excluded the operant physical effects.

Third, a series of experiments conducted in the early 1980s gave positive results showing the effect existed [16–18], but at a low rate that seemed to be inconsistent with theoretical predictions. It was this conundrum, perhaps more than anything else, that led to the suspension of work on low-frequency CW acceleration of radioactivity. These experiments have been revisited with the assistance of the DOE support, and it is now clearly understood that the electromagnetic conditions selected for the experiments were inappropriate. More specifically, the externally applied electromagnetic environments in the early experiments are now seen to be entirely consistent with theoretical predictions.

In the following sections, the basic physical mechanisms underlying the interaction of the low-frequency intense applied fields with the nucleus will be reviewed first. Each of these mechanisms can be identified with certain elements of the theoretical formulation of the problem. The capability to make this identification lies at the heart of the results accomplished with the DOE grant.

Then a brief review of the new theoretical formulation of the quantum-mechanical of accelerated beta decay will be presented, in which some of the quantitative aspects of the physical mechanisms for radioactivity acceleration can be identified with a clarity not previously possible. This work has so far been reported only very incompletely [19], but it is ongoing [20], and will be reported upon more fully in the near future.

In light of the above results, the reasons for the irrelevance of the negative conclusions reported earlier will be made clear.

Then, the early experiments will be reviewed, and their implications for the correctness of the theoretical predictions can be given a quantitative basis. Most, importantly, the re-analysis of the experiments points the way towards a proper selection of experimental conditions for a future round of "proof-of-principle" experiments.

A "Conclusions" section will point the way to the next steps that must be taken.

III. QUALITATIVE STRONG-FIELD EFFECTS

The type of beta decay radioactivity that we treat is always of the β^- type, and never β^+. The reason is that we are concerned with disposal of high-level radioactive waste (radwaste), and all fission fragments are neutron-rich. That is, to approach nuclear stability, all radioactive decays within the nucleus convert a neutron n into a proton p according to the scheme

$$n \rightarrow p + e^- + \overline{\nu_e}.$$

In this expression, the β^- particle is recognized as a simple electron e^-, and $\overline{\nu_e}$ is the electron anti-neutrino that is the associated lepton emitted in the beta decay. Hereafter, we shall simply refer to the decay electron or beta particle β without identifying it as negatively charged, and $\overline{\nu_e}$ will simply be identified as a neutrino ν, without further particulars.

A. Field-induced beta-particle motion

When beta decay occurs in the presence of an intense electromagnetic field, the electron must behave as a free particle influenced by that field. It is well known [21,22] that, in a linearly polarized plane-wave field, the electron is forced to execute a figure-8 pattern in which the long axis of the 8 is along the direction of the electric field, and the short axis is aligned with the direction of propagation of the field. That is, the figure-8 lies in a plane perpendicular to the direction of the magnetic field. The proportions of the figure-8 are determined by a single intensity parameter characterizing the field, and these proportions are maintained even in the limit as the field wavelength becomes very large. This intensity parameter,

$$z_f = 2U_p/mc^2,$$

is a basic parameter of field-accelerated beta decay. The quantity U_p, the ponderomotive energy, is the energy that the electron must have because of its field-induced motion. It is not surprising that this energy is to be compared to the rest energy mc^2 of an electron. It is only when the field is so strong that field-induced energy is competitive with rest energy that the field is capable of altering beta decay behavior. We find that this z_f parameter should be about of the order of 10 to create optimum conditions for the acceleration of beta decay.

The essential element in field-induced introduction of angular momentum is that the field be a plane-wave field and not a quasi-static electric field. The magnetic component of the plane-wave field is vital, even though it is customary to neglect it for most purposes. Since the wavelength is very much larger than the size of the nucleus, and the dimensions of the figure-8 are of the order of the wavelength, the question naturally arises about the location of the electron in the pattern at the time of its emission. It can be shown that the probability of the beta decay is independent of the phase of the electromagnetic wave at the time of decay. This is usual in quantum problems where, unlike classical problems, initial conditions are irrelevant. The electron can then be viewed as appearing randomly over the classical phase, which means that there are large proportions of each wave period in which the electron must exhibit a truly large field-induced angular momentum. This will be true even though an averaging over the complete figure-8 will result in a cancellation of angular momentum. In the quantum problem, interaction with other parts of the system will de-phase the electron long before it could ever execute the complete figure-8. We emphasize that this description is simply a qualitative discussion of the results of the definitive quantum-mechanical solution of the problem.

B. Spin flip and virtual pairs

A special characteristic of the electron as a spin-$\frac{1}{2}$ quantum particle is that a very intense field will, with intensity-dependent probability, "flip" its spin to a direction opposite to that of its original orientation. We have found this phenomenon to constitute an important alteration of angular momentum selection rules governing the probability of beta decay in a strong field as compared to an environment that does not include a strong field. It presents a new "allowed" channel in an otherwise forbidden beta decay.

This spin-flip term is clearly in evidence in the Volkov solution [7] that describes the quantum state of a free electron (that is, the emitted beta particle) in the presence of a plane-wave field. The term that produces this behavior also has the effect of producing "virtual" electron-positron pairs. Explicitly, this term appears in the Volkov solution as the second term in

$$1 + z_f^{1/2} \frac{\gamma^\mu p_\mu \gamma^\nu A_\nu}{p^\lambda k_\lambda},$$

where the γ^μ four-vector gives the four independent Dirac matrices, p^μ is the four-momentum of the electron, and A^μ is the four-vector potential of the plane-wave field with propagation four-vector k^μ. It is easily shown that this second term acting on a spin-up positive-energy electron will, when the intensity parameter z_f is sufficiently large, produce important components of spin-flipped electrons as well as virtual pairs. These virtual pairs never appear in the final state in the laboratory, so they are not directly detected, but their presence alters the angular momentum properties of the field-accelerated beta decay. This opens new decay channels where none existed in the absence of the field.

C. Angular momentum broadening of nuclear states

Under ordinary circumstances, the angular momentum state of a nucleus is well defined, and is a standard identifying characteristic of any particular nuclear state. It is the change in angular momentum in going from an initial state before the beta decay to the final state arrived at after the decay that serves to establish the selection rules. In quantum parlance, angular momentum is a "good" quantum number for a nuclear state.

When the nucleus is immersed in a sufficiently strong field, as measured by the appropriate intensity parameter (similar to the z_f identified above), then angular momentum ceases to be a good quantum number. This "smearing" of the angular momentum properties of the nuclear state, is given explicitly by [23]

$$\Psi = \Phi \sum_{l=0}^{\infty} i^l (2l+1)\, j_l \left(c z_f^{1/2} r \cos(\omega t) \right) P_l (\cos\theta),$$

where Ψ is the nuclear quantum state Φ after being modified by the applied field. The function j_l is a spherical Bessel function, P_l is a Legendre polynomial, r and θ are spherical coordinates, ω is the circular frequency of the applied field, and c is a constant (dependent on the nuclear radius) that is of the order of 10^{-2}. When the argument of the spherical Bessel function is of order unity, then a nuclear state acquires a strong admixture of angular momentum substates. This leads to the opening of many new decay channels, some of which will correspond to allowed decays.

The consequence will be a decrease of the beta decay half-life.

D. Overview of rate acceleration mechanisms

We have found the field-induced figure-8 motion of the beta decay electron to be the most important contributing effect in beta-decay enhancement. Spin-flip and virtual pair creation are nearly as major in their contributions, gaining in relative influence as the intensity increases. So far, smearing of the nuclear states appears to have the least overall effect, although it is possible that the accelerated decay rates will exhibit a second maximum at higher intensities than the one we have found. For the smearing of nuclear angular momentum states to serve as a decay-acceleration mechanism, requires the greatest intensity of the three factors we have listed.

IV. EXPLICIT THEORETICAL DEVELOPMENTS

A. Polarization of the applied field

1. The appeal of circular polarization for intense-field processes

As a preamble to any serious attempt to do explicit calculations of field-enhanced beta decay, it is necessary to recognize that the polarization state of the applied field is of paramount importance. Failure to do so has led to sweeping conclusions that are not correct.

Non-perturbative, intense-field calculations are always easier to carry out for the effects of a circularly polarized field This is true even for atomic problems [12], where one can employ the dipole approximation for the field. This can be easily seen from the non-relativistic squared kinetic momentum operator $\left(\mathbf{p}-\frac{q}{c}\mathbf{A}\right)^2$. Suppose the vector potential $\mathbf{A}$ of the applied field has the simple form

$$\mathbf{A}=\frac{1}{2}a\left(\epsilon e^{i\omega t}+\epsilon^* e^{-i\omega t}\right).$$

For circular polarization, the unit polarization vector ϵ is complex with the properties

$$\epsilon^2=\epsilon^{*2}=0,\;\; \epsilon\cdot\epsilon^*=1,$$

so that $\mathbf{A}^2=a^2/2$, nothing more than a constant. For linear polarization, with ϵ real, then

$$\mathbf{A}^2=a^2\cos^2\omega t=\frac{a^2}{2}+\frac{a^2}{2}\cos 2\omega t.$$

The resulting double-frequency term $\cos 2\omega t$ coexists with single-frequency terms from $\mathbf{A}\cdot\mathbf{p}$ and $\mathbf{p}\cdot\mathbf{A}$ operators. That simple fact makes strong-field non-perturbative calculations vastly more complicated for linear (or elliptical) polarization than it is for circular polarization of the field. As a consequence, it has become common practice to assume circular polarization when exploring any new phenomenon, where it is important to keep analytical complexity from obscuring the real physics of the problem.

The double-frequency term exhibited above in the simple dipole-approximation case occurs also in the relativistic case where full spatial dependence must be retained along with the time dependence. This remains true even in the Dirac relativistic case, where the equation of motion appears to be linear in the field. As might be expected, the $\mathbf{A}^2$ term nevertheless appears in the phase of the resulting (Volkov) wave function.

As will now be discussed, simplifying the calculation of extremely high-order processes by assuming circular polarization is truly a case of "throwing the baby away with the bath water".

2. Disqualifying features of circular polarization

When the beta decay electron emerges from the nucleus, it will find itself immersed in an intense, low frequency field. There are many classical features to this situation. Classical arguments give much insight into why circularly polarized fields have no effect on beta decay rates.

For large intensity parameter z_f as defined above: $z_f = 2U_p/mc^2$, the minimum "photon order" of possible electromagnetic interactions with the beta decay nucleus is given approximately by the number of photons necessary to supply the ponderomotive energy U_p. That is, $N = O\left(mc^2/\hbar\omega\right)$. For the frequencies that are found to be necessary for successful acceleration of beta decay, $N = O\left(10^{15}\right)$. The matrix element for a transition from a state with an angular momentum that is initially of the order $L/\hbar = O\left(1\right)$ to an angular momentum state with $L/\hbar = O\left(10^{15}\right)$ is plainly going to be zero.

A quantum-mechanical way to view the problem is to note that each circularly-polarized photon absorbed will increase the m quantum number (as given by the Y_l^m spherical harmonics) by a single unit. That then forces the l quantum number to increase by one unit for each photon, agreeing with the classical result of an increase in the quantum number l by $O\left(10^{15}\right)$. There is no such limitation with linearly polarized photons. For large photon orders, the quantum transition rates will be in the ratio $N^{3/2}/2^N$ for circular polarization as compared to linear polarization [24]. This is an astoundingly small number for $N \approx 10^{15}$. Whereas the numerator in this ratio gives the large, but relatively ordinary result $N^{3/2} \approx 10^{23}$, the denominator gives $2^N \approx 10^{.3N} \approx 10\hat{}\,(3*10^{14})$. This is a number that is inconceivably large. It is between the famed, whimsically named "googol" (10^100) and "googolplex" (10^(10^100)). The googol was invented to represent an inconceivably large number, which nevertheless fades to smallness in the face of the googolplex. Since 2^N is in the denominator of the circular-to-linear-polarization ratio, the rate for circular polarization is zero.

That is, there is no accelerated beta decay channel possible when circularly polarized fields are employed. This is a basic result that was not appreciated before the research performed under this grant.

B. Nuclear matrix element for accelerated beta decay

The structure of the accelerated beta decay matrix element is particularly instructive. With no applied field present, the nuclear current factor in the beta decay matrix element has the form

$$M_{fi} \sim \langle \Psi_f | \exp\left[i\left(\mathbf{p}_e + \mathbf{p}_\nu\right)\cdot\mathbf{r}\right] |\Psi_i\rangle ,$$

where Ψ_i and Ψ_f are the initial and final nuclear states, and $\mathbf{p}_e + \mathbf{p}_\nu$ is the sum of the electron and neutrino three-momenta. The vector $\mathbf{r}$ is bounded in magnitude by the size of the nucleus. For typical energies released in a beta decay, the magnitude of the argument of the exponential, $|(\mathbf{p}_e + \mathbf{p}_\nu)\cdot\mathbf{r}|$, is about 10^{-2}. It is thus justified to expand the exponential as

$$\exp\left[i\left(\mathbf{p}_e + \mathbf{p}_\nu\right)\cdot\mathbf{r}\right] \approx 1 + i\left(\mathbf{p}_e + \mathbf{p}_\nu\right)\cdot\mathbf{r}.$$

If the beta decay is allowed, then the nuclear matrix element follows from the first term in the expansion. If the beta decay is first-forbidden, then the leading term in the expansion yields a zero result, with the primary contribution then arising from the second term in the expansion of the exponential. As pointed out, this has a typical magnitude less than that of the first term by a factor 10^{-2} in the matrix element (or transition rate). The transition probability then suffers a reduction by a factor of about 10^{-4} as compared to an allowed decay.

The new theoretical results we have obtained in our research yields a field-modified nuclear matrix element that analytically resembles the no-field case. We find the matrix element

$$M_{fi} \sim \langle \Psi_f | \exp\left[i\left(\mathbf{p}_e + \mathbf{p}_\nu\right) \cdot \mathbf{r} + if\left(z_f\right) \widehat{\epsilon} \cdot \mathbf{r} + ig\left(z_f\right) \widehat{\mathbf{k}} \cdot \mathbf{r} \right] |\Psi_i\rangle ,$$

where $\widehat{\epsilon}$ is a unit vector in the direction of the electric field vector, $\widehat{\mathbf{k}}$ is a unit vector along the direction of propagation of the field, and f and g are functions of the intensity parameter. The f part comes partly from the Volkov solution and partly from nuclear-state smearing, while the g part is entirely from the Volkov solution. The f and g functions are bounded from above, with bounds that depend on many factors, but are generally somewhat larger than $|\mathbf{p}_e + \mathbf{p}_\nu|$. For the same reasons as the $\left(\mathbf{p}_e + \mathbf{p}_\nu\right) \cdot \mathbf{r}$ term measures the amplitude of the first-forbidden beta decay matrix element, then so does $\left(\mathbf{p}_e + \mathbf{p}_\nu\right) \cdot \mathbf{r} + f\left(z_f\right) \widehat{\epsilon} \cdot \mathbf{r} + g\left(z_f\right) \widehat{\mathbf{k}} \cdot \mathbf{r}$ measure the field-enhanced amplitude.

Other aspects of the complete analytical expression for the transition amplitude also contribute to field enhancement of the decay. Numerical calculations so far have employed only very simple models for nuclear wave functions [20], but indications are that a factor of ten enhancement in decay rate might be possible. If further calculations bear out that expectation, this is a major result indeed.

C. Numerical prediction

Although the analytical structure is now in good shape, the magnitude of the effect must be determined with clarity. This is necessary both to ascertain the level of difficulty in making practical application of accelerated beta decay, as well as for making wise choices in the selection of parameters for experiments and applications.

After carrying analytical formulation as far as possible, there remains a need for a final numerical four-fold integration over the phase space of the emitted leptons. This poses the difficulty that the boundaries of the integration in the necessary four-space are very complicated, compounded by the fact that most of the contribution to the integrals comes from integrable singularities at the boundaries. Conventional numerical integration approaches are not designed for such a problem. Hongan Wang, a Ph.D. student supported by this grant, first attempted to revise existing multiple-integration Fortran codes that have been carefully checked by others. The integrable-singularity property over complicated boundaries foiled this attempt. He then developed C++ code for this purpose. This is novel work [20]. We have been unable to find anything comparable in the literature.

This work remains incomplete, but some preliminary results have been obtained based on very simple analytical models for the nuclear wave functions. Interestingly, the outcome so far is quite similar to numerical results arrived at in earlier work [3], even though there were many layers of approximation employed in that work that are now avoided. In short, the optimism for successful applications that were a result of the 1983 papers [2,3] are sustained by the new work.

V. CONTRARY CALCULATIONS

The appearance of the two 1983 papers by the PI [2,3] stimulated activity by other researchers to repeat the calculation by their own methods. This led to a confused situation, since the essential physical elements of the calculation were not clear in the 1980s. The complexity of the theoretical work masked the true nature of the effect, with much of the claim and counter-claim ill-focused. We are now in a position to assess the situation with clarity. We examine the negative results of three different approaches. The conclusion is that each of them is incorrect and/or irrelevant based on the considerations summarized above.

A. Work of Akhmedov

From our new perspective, the work of Akhmedov [14] is especially easy to analyze. He employs a dipole-approximation non-relativistic Volkov solution. The dipole approximation means that the phase of the applied electromagnetic field, $\omega t - \mathbf{k} \cdot \mathbf{r}$, is replaced simply by ωt. There can be no figure-8 motion, thus excluding the first mechanism for beta decay acceleration.

The use of non-relativistic Volkov solutions means that there is no spin-flip and no possibility of virtual pairs. The second mechanism for beta decay acceleration is therefor absent.

The nuclear states are treated by perturbation theory. If the field is unable to provide enough energy to approach at least a near resonance with an excited state in the initial or final nuclear state, then no transition can occur. No near-resonances are possible, and so no effect could possibly have been found.

Circular polarization of the field is assumed. This in itself, as pointed out above, precludes any possibility for accelerated beta decay.

B. Work of Becker, Schlicher, and Scully

Becker, Schlicher, and Scully [15] employ the procedures of Akhmedov in most respects. They use a dipole-approximation Volkov solution (no figure-8), that is non-relativistic (no spin-flip, no virtual pairs), and for circular polarization (null result guaranteed).

C. Work of Friar and Reiss

Friar and Reiss [13] employed circular polarization on the grounds of analytical tractability. The work found no acceleration of rate, with the decay electron appearing through the usual forbidden-decay channel, followed by field-induced distortion of the electron phase space. As shown above, the null result was fore-ordained by the choice of circular polarization for the field.

VI. RE-ANALYSIS OF EARLY EXPERIMENTS

A major outcome of this DOE-sponsored research is an understanding of experimental results obtained years ago. Some of the experiments were done before any open publication of the theory.

There is one point of similarity that connects all the experiments. Each used a 10 μCi ^{137}Cs source in the form of CsCl, encapsulated in a plastic retainer. The use of a solid-state source suggested a possible problem from the outset. The theory is very firm on the necessity for both electric and magnetic components of the applied field. Simple oscillating electric fields cannot induce the basic physical phenomena described above. On the other hand, neither can simple oscillating magnetic fields. The problem here is the cloud of atomic electrons that surround the nucleus. They will have no significant effect on the magnetic field, but classical arguments suggest that atomic electrons will respond to the externally applied field in such fashion as to cancel that field.

A. First University of Arizona experiments

It was decided in 1980 to test the matter empirically [16]. The ^{137}Cs source was attached to the outer surface of the inner conductor in a large (three-inch diameter) coaxial transmission line used to feed the antenna in a relatively high-powered AM radio station operated by the University of Arizona. The result was ambiguous for two reasons.

One difficulty came from the fact that experimental results did not support either of the two sets of expected results. The conditions in the coaxial line were estimated to be such as to produce a major change in decay rate if the atomic electrons provided no shielding. If the atomic electrons shielded the nucleus from the field, a null result was expected. The final result was that a rate acceleration of the order of one part in 10^3 was found. A small but non-zero answer could not be explained at the time.

The second problem was that too many possible systematic sources of error existed. We carried out experiments in the dusk-to-dawn portion of the day with a radio station that operated on a dawn-to-dusk transmission schedule. The radio transmitter was operated for our experiments in a cycle of about fifteen minutes of power on followed by fifteen minutes of power off. It was evident that heating of the transmission line caused changes in source-detector distance that influenced the results. These effects had to be measured and removed, which then introduced too great a possibility of systematic error.

B. Amoco Research laboratory experiments

A second set of experiments was done at the Amoco Research Laboratory in Napersville, IL in 1981 [17]. A coaxial cavity operated at 4.4 MHz was used. The heating problem was solved by attaching a reference source to the inner conductor immediately adjacent to the ^{137}Cs source. The reference source had an allowed beta decay followed by a gamma ray that was well displaced in energy from the 662 keV gamma ray that follows the beta decay of ^{137}Cs. Both gamma lines were detected with the same detector, and results evaluated from a ratio of the counts of the two sources. This definitely removed effects from source-detector distance changes, but the final result of data analysis was a relative acceleration of rate by $(8.8 \pm 4.1) \times 10^{-4}$.

Again, there was no understanding of the reason for a small but non-zero result. There was also the difficulty that all calculations had been done for a traveling plane wave, and the experiment used a cavity. There was no means of determining if this was germane.

C. Second University of Arizona experiments

A third set of experiments involved a return to the KUAT radio transmitter at the University of Arizona in 1983-84 [18]. This time a comparison source was used, attached to the inner side of the inner conductor, directly behind the ^{137}Cs source on the outer side of the inner conductor. This placed the comparison source in a field-free region to remove any possibility of its rate being influenced by the field. The field frequency at KUAT is 1.55

MHz. Relative decay rate acceleration of $(6.5 \pm 2.0) \times 10^{-4}$ was found. This was consistent with the Amoco results, but did not resolve the dilemma of the too-small but non-zero result.

D. Catholic University experiments

A fourth set of experiments in 1988 at Catholic University of America in Washington, DC was aborted. We were unable to acquire the planned electronics for a multiple-detector, computer-operated and computer-analyzed experiment designed to achieve very small statistical errors in the result. A coaxial transmission line was again used with a ^{137}Cs source, but the field frequency was reduced to $200\,kHz$, albeit with about the same z_f values as in previous experiments. Although the lack of the planned equipment stymied the intended purpose of this experiment, enough data were taken to reveal a decay acceleration of about one part in 10^3, consistent with all the earlier work.

E. New interpretation of all experiments

Work on beta-decay acceleration was suspended in 1988. It was renewed at the time of the DOE grant because a fresh look at the theoretical aspects of the problem began to reveal the understanding outlined above of the basic strong-field effects underlying beta decay acceleration.

A fresh look at the experiments revealed a crucial insight that had previously eluded us. The ^{137}Cs source was in the form of a $CsCl$ crystal, which is a tightly bound alkali-halide crystal. A look at the possibility of phonon excitation in the crystal lattice revealed that such excitations are impossible with the fields applied. What this means is that each cesium atom in the crystal has donated its valence electron to the crystal, leaving behind what is, in essence, a singly ionized Cs ion. A simple classical argument can be used to show that atomic electrons cannot completely prevent an externally applied field reaching the nucleus. The electric field strength at the nucleus is approximately the fraction $1/Z$ of the field strength before atomic-electron shielding, where Z is the electric charge of the nucleus. For cesium, the nuclear charge is $Z = 55$. Qualitatively, what is happening is that application of an external field causes a re-alignment of the atomic electrons such as to maximally cancel the applied field at the nucleus, but the lack of the valence electron makes complete cancellation impossible.

The consequence is that the intensity parameter z_f is effectively only $1/(55)^2 \approx 3 \times 10^{-4}$ of the intended z_f. Although the acceleration of the beta decay rate is not simply proportional to z_f, nevertheless the experimental results obtained are no longer a mystery. The electromagnetic conditions employed in the experiments were designed to provide an unduly small z_f, leading to an unforeseen small outcome.

F. Consequences of the new interpretation

There are now four sets of experiments giving mutually consistent results, albeit with only two of them [17,18] subjected to a comprehensive statistical analysis. Each experiment employed nearly the same z_f value, even though field frequencies ranged from a high of 4.4 MHz to a low of 200 kHz. This is strong evidence for the validity of the theoretical prediction that beta decay acceleration is measured only by that particular combination of field strength and frequency that occurs in z_f.

Most importantly, those old experiments, some of them done twenty years ago, can be regarded as a proof of principle for the possibility of rf-field induced acceleration of forbidden beta decay.

VII. CONCLUSIONS AND NEXT STEPS

The entire analytical formulation of the theory of accelerated beta decay has been reworked from the beginning. This is a major task, since it is far more demanding than the theory for spontaneous beta decay, and it requires a thorough knowledge of non-perturbative calculational techniques. These non-perturbative methods are very different in method and in physical insight than are standard perturbation theory methods. (The basic strong-field technique for unbound charged particles was pioneered by the PI [8], and the strong-field low-frequency "dressing" method for bound states was also introduced by the PI [25,23].) In its new form, the content of the theory is far more transparent than in previous work [2,3], and so it has become possible to identify the explicit physical phenomena underlying the effect.

Armed with the new-found clarity about the mechanisms for accelerating forbidden beta decay, it is now possible to understand how different researchers came to such different conclusions, and to identify explicitly which theories were germane and which were wide of the mark. The end result is a renewed confidence in the implications of the theory for eventual practical applications.

Much theory remains to be done. If some analytical way can be found to reduce the number of integrations that remain for numerical evaluation at the end of the problem, the power of the theory is correspondingly enhanced. This is urgently needed for the choice of experimental parameters and/or the design of practical systems employing these ideas.

The foremost need at this point is to execute a new round of "proof-of-principle" experiments employing the new-found understanding about the appropriate choice of intensity parameter. The best that can be done at the moment is to choose an order of magnitude for the intensity parameter, and then to optimize it empirically.

More theory is needed to examine in some detail the screening effect of atomic electrons in keeping the full magnitude of the applied field from reaching the nucleus. The simple classical model used so far will have to be refined. Furthermore, the $CsCl$ crystal structure that has so far been the subject of attention is probably the simplest physical arrangement that will occur. For example, oxides will be much harder even to estimate.

There is definitely more theory needed to explore whether the option even exists for obtaining primary energy from the acceleration of forbidden beta decay. Although the present work has been focused primarily on the reduction of high-level wastes from fission, there exists the enticing prospect of nuclides whose beta decay is so highly forbidden (and half-lives so long in consequence) that they remain in the Earth's crust from the time of formation of our planet. The energy locked up in these materials is an inherent energy resource whose release would vastly enlarge civilization's total energy resources. The method for this release, if it is feasible, avoids all of the collateral radioactivity that plagues fission power, and even (to a lesser extent) prospective fusion power.

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