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# A GENERAL FORMULA FOR THE DECAY LIFETIMES OF THE STARFISH ELECTRONS

*by*

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16. Abstract

A treatment based on the analysis of data from Satellite 1963 38C has been developed to calculate the decay lifetimes of the artificial electrons produced by the Starfish nuclear explosion. The treatment makes use of experimental data and describes the decay lifetime $\tau$ in the form of a continuum in *BLE*-space. The results are valid over the entire inner zone of the trapped radiation belt. Reference maps of constant $\tau$ contours in *BL*-, *BE*-, and *LE*-space have been constructed and are discussed.

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## INTRODUCTION

Seven artificial radiation belts have been made by the explosion of high-altitude nuclear devices since 1958. Of these, the Starfish event of July 9, 1962, a low-latitude nuclear explosion, produced an intense region of trapped artificial electrons with very long lifetimes.

The spatial and temporal characteristics of the artificial radiation zone have received considerable treatment in the literature, and the decay lifetimes for the injected electrons have been discussed by several authors (Van Allen, 1964; Cladis et al., 1965; Bostrom and Williams, 1965; Brown, 1966; McIlwain, 1966; Paulikas et al., 1967; Beall et al., 1967; Pfitzer, 1968; Bostrom et al., 1970). The picture that emerges is that of a fast decay at very low $L$ values ($L \leqslant 1.2$), which is consistent with the predictions of atmospheric scattering theory (Walt, 1964). Short lifetimes also occur at the outer edge of the inner radiation zone in the slot region. For the intermediate $L$ values, the decay is slower, with longest lifetimes occurring at $L \sim 1.4$. At low $L$ values ($1.15 \lessapprox L \leqslant 1.4$), a $B$-dependence is also observed (Beall et al., 1967).

In the years following 1962, computer programs were developed at GSFC to estimate the flux decay of artificially injected electrons and predict the radiation hazards to which satellites would be exposed (Stassinopoulos, 1965, 1967). The decay lifetimes used in the calculation of orbit-integrated, vehicle-encountered particle fluxes were based on fragmentary published data, and as such they were restricted and not very accurate (Stassinopoulos, 1965). In this paper a unified treatment of the decay of the artificial electrons in the inner zone is presented, with the decay lifetime $\tau$ expressed as a continuous function of field strength $B$, magnetic shell parameter $L$, and energy $E$. The data used in the analysis is essentially taken from a single satellite, the 1963 38C,† and covers the time span from

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launch, September 28, 1963, to December 1968, when, it is felt, the energy channels of the satellite measured essentially the radiation of the natural background (Bostrom et al., 1970). A description of the satellite and its instrumentation can be found in the literature (Williams and Smith, 1965; Bostrom et al., 1967; Beall et al., 1967).

## DISCUSSION

In order to facilitate the handling of the problem, the following simplifying assumptions are made:

(1) The decay lifetime $\tau$ remains constant in time.

(2) Solar-cycle, diurnal, and secular-change effects can be neglected.

(3) The decay of the Starfish electrons can be approximated by an exponential form.

(4) The $B$-dependence of $\tau$ does not extend beyond $L \geqslant 1.40$.

Assumption (3) is justified by the 1963 38C data; assumption (4) is supported by comparison with OGO data, which measures a wider range of equatorial pitch angles than does 38C (Pfitzer, 1968; Pfitzer and Winckler, 1968).

When the data is ordered in terms of the variable $L$, three distinct regions emerge (Figure 1), each identified by a characteristic functional dependence of $\tau$ on the parameters $B$, $L$, and $E$. We denote

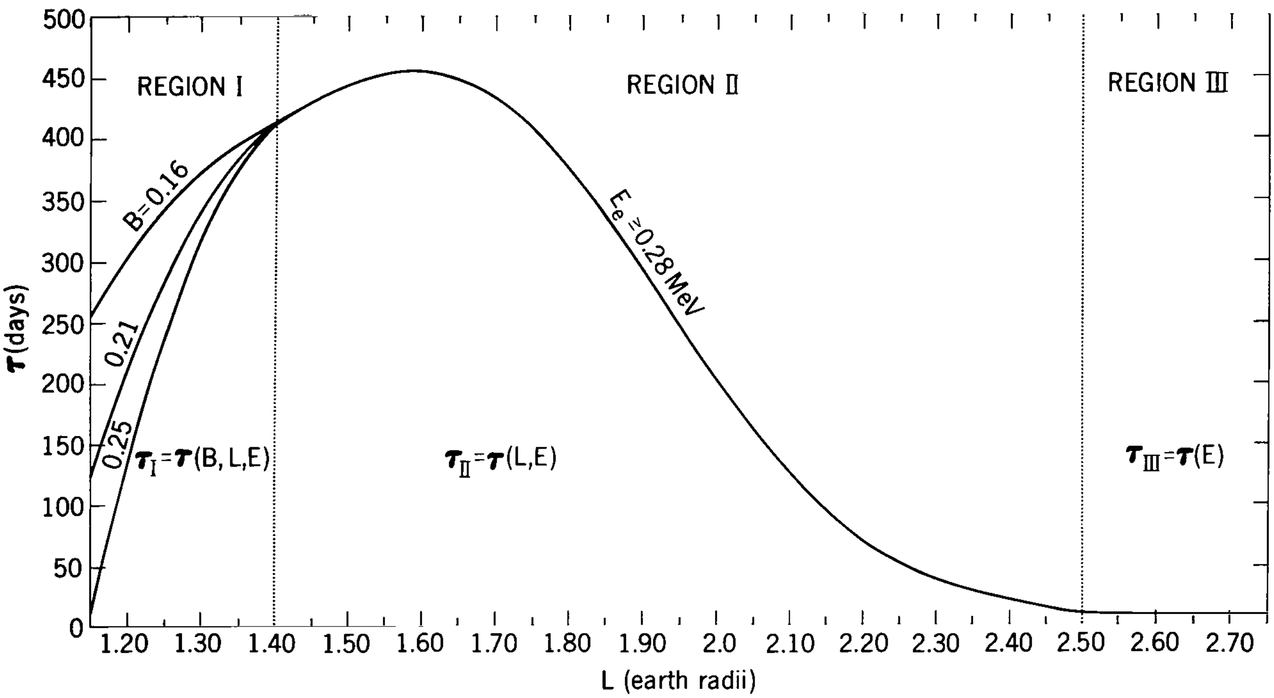


Figure 1—Domains of functional dependence of the decay lifetime $\tau$ on $B$, $L$, and $E$ for $E_e \geqslant 0.28$ MeV.

the three regions as I, II, and III. In region I, which extends from $L = 1.15$ to $L = 1.40$ (for all electron energies), $\tau$ is a function of all the variables: $B$, $L$, and $E$. The $B$-dependence of the decay constant has been previously discussed by Beall et al. (1967), and it appears to become indeterminate for $L \gtrsim 1.4$. Consequently, in our treatment we will take $\tau$ in region II to depend only upon $L$ and $E$. Region II extends from $L > 1.4$ to approximately $L \sim 2.3$, with the latter boundary being dependent on energy. Curves obtained for region II from the 38C data when $\tau$ is plotted versus $E$ for all three channels at given $L$ values suggest that the high-energy electrons exhibit the most rapid decay and that at the time of the 1963 38C measurements almost no artificial electrons with energies greater than 2 MeV remained in regions where $L \gtrsim 1.8$. This is in general agreement with currently prevailing opinion* (Pfitzer, 1968). Thus, in the generation of the $\tau$ versus $E$ plots for region II ($1.4 < L \leqslant 2.3$), no data from the 1963 38C channel 3 ($E_e \geqslant 2.4$ MeV) were used; instead, the $\tau$-dependence was extended linearly to the higher energies, with only data obtained from channels 1 ($E_e \geqslant 0.28$ MeV) and 2 ($E_e \geqslant 1.2$ MeV) being used. This is consistent with the derivation of the decay lifetimes obtained by Beall et al. (1967) and reflects the uncertainty in the channel 3 data due to background proton contamination. At the higher $L$ values ($L > 1.8$) in this region, the data were adjusted to fit reported measurements (Van Allen, 1966; McIlwain, 1966; Brown, 1966).

Finally, in region III, which includes all $L$-space beyond about 2.3, the decay lifetime was taken to be only a function of energy. In this region, $\tau$ is typically of the order of one month or less and will be neglected in this treatment. Figure 1 outlines the domains of the regions discussed above for electrons with $E_e \geqslant 0.28$ MeV and indicates the dependence of $\tau$ on the variables appropriate to each domain.

In the formulation of this problem, a four-dimensional space is considered in which the decay lifetime $\tau$ is a continuous function of the variables $B$, $L$, and $E$. The boundaries beyond which computation of $\tau$ is discontinued are:

(1) The equatorial envelope, as defined by McIlwain (1961).

(2) The radiation-belt terminus, designated as the constant-electron-intensity contour of one particle per square centimeter per second, for trapped electrons with energies greater than 0.5 MeV, as given by Vette et al. (1966).

(3) The surface $\tau = 0$.

It is assumed that the terminus is independent of time and energy in $BL$-space, since any slight changes in its position due to energy dependence or secular variations do not affect the derivations and conclusions presented in this treatment. The four-dimensional space is then subdivided into volume elements such that within each volume the parameter $\tau$ may be linearized for each of its variables (i.e., all partial derivatives of $\tau$ are constant).

Since the decay constant depends mainly on the magnetic shell parameter $L$, appropriate increments in $L$ have to be taken so as to preserve the linearity requirement for the derivatives of $\tau$ within each volume element. Thus, region I is subdivided into 11 $L$-intervals and region II into 19 $L$-intervals.

*J. I. Vette, private communication, 1970.

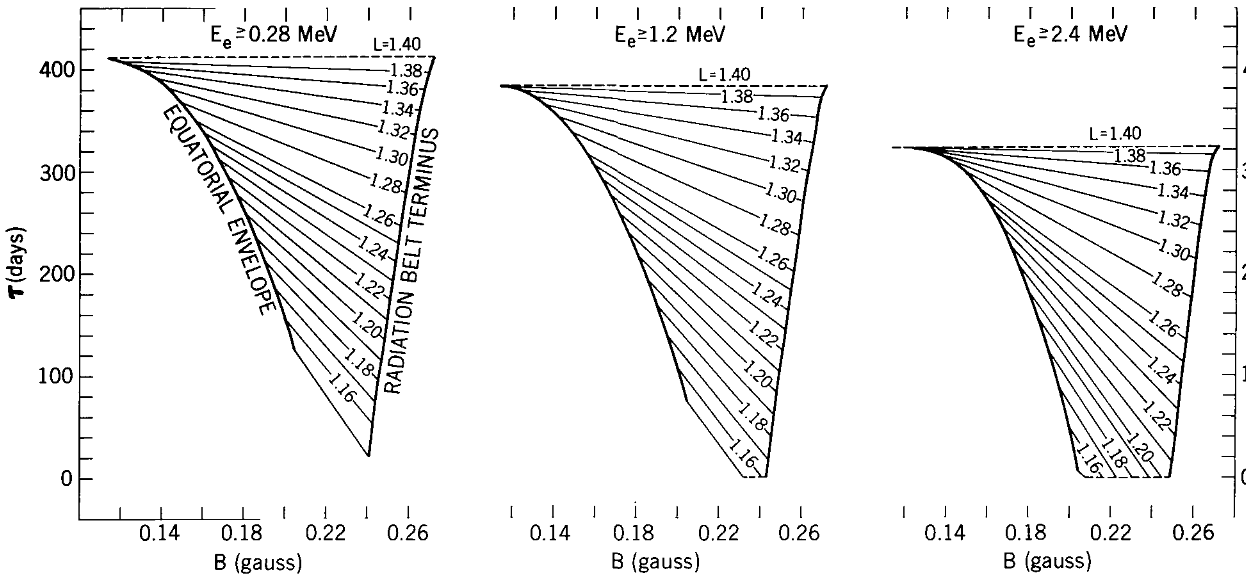


Figure 2—Decay lifetimes in region I ($1.15 \leqslant L \leqslant 1.4$) showing the $B$ and $L$ dependence of $\tau$ for the 1963 38C satellite energy channels.

Figure 2 shows the dependence of $\tau$ on the variables in region I for the three energy channels of satellite 1963 38C. In the next two figures, several cross sections of the $\tau$ domain in region I are plotted. Figure 3 shows $B$-$L$ cross sections for $E_e \geqslant 0.25$, 0.5, 1, and 3 MeV; Figure 4 shows several $B$-$E$ cross sections at four discrete values of $L$. In both figures, the dependence of $\tau$ on $B$ at these low values of $L$ is clearly evident. Figure 5 shows the dependence of $\tau$ on $L$ and $E$ in region II. The slowest decay in this treatment occurs at $L \sim 1.6$ for $E_e \sim 0.3$ MeV. The peak in the $\tau$ contours gradually drifts toward $L \sim 1.4$ at the higher integral energies. Curves for $\tau$ are not plotted for $E_e < 0.2$ MeV because there is evidence that the low-energy component ($E_e \sim 0.1$ MeV) of the integral electron flux does not manifest a perceptible decay (Pfitzer, 1968; Pfitzer and Winckler, 1968).

## DATA PROCESSING

A generalized treatment for all three variables as they pertain to region I will be given here. The same treatment, appropriately modified to deal with only two variables, applies to region II. In general,

$$\tau = \tau(B, L, E) . \tag{1}$$

The following relations then hold within each volume element:

$$\tau = \kappa(B,L)E + \lambda(B,L) , \qquad \kappa = \frac{\partial \tau}{\partial E} = \mu(L)B + \nu(L) ,$$

$$\nu = \gamma L + \eta , \qquad \mu = \frac{\partial^2 \tau}{\partial B \partial E} = \alpha L + \delta , \tag{2}$$

$$\alpha = \frac{\partial^3 \tau}{\partial L \partial B \partial E} ,$$

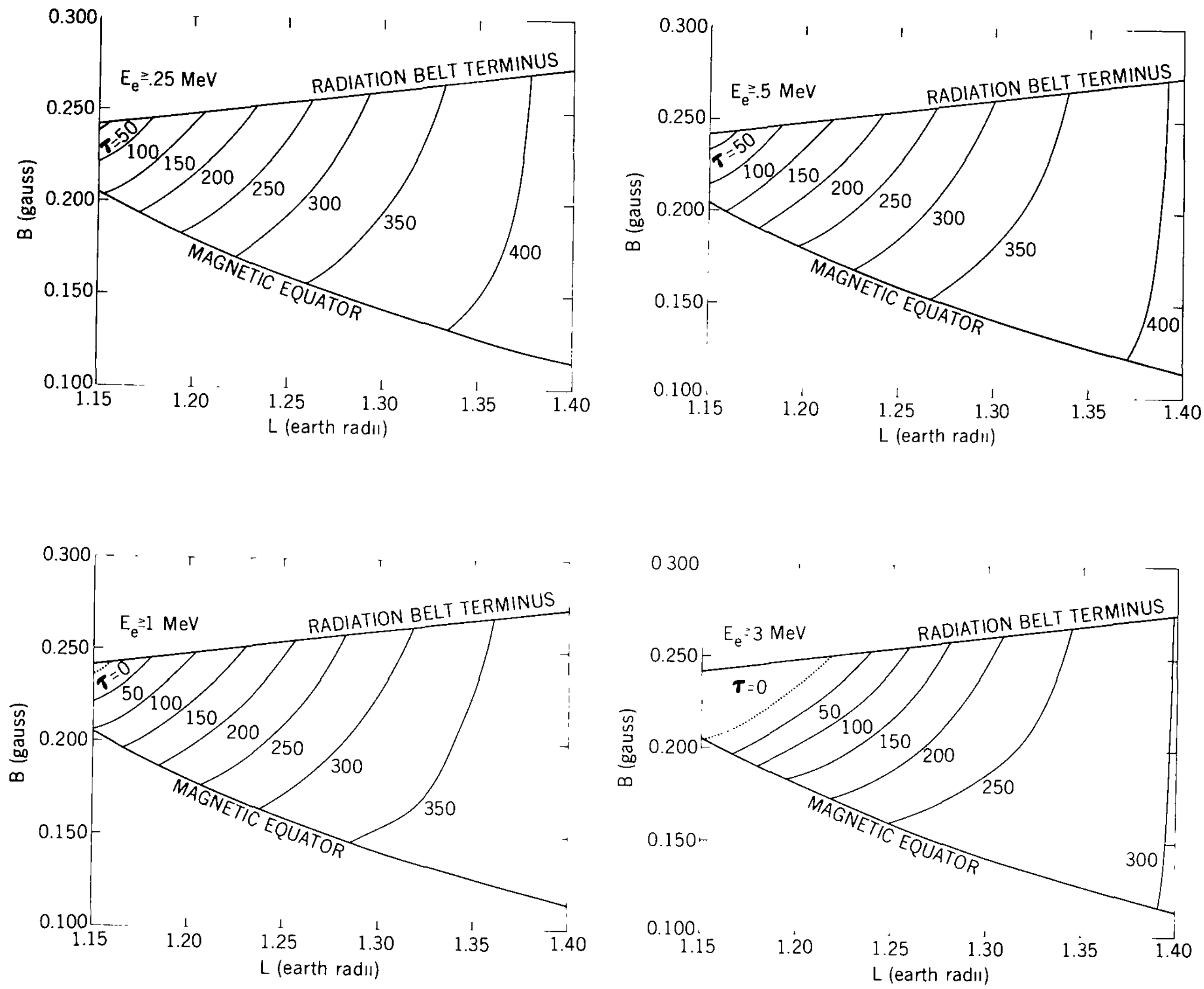


Figure 3—$BL$ cross sections of the $\tau$ domain in region I ($1.15 \leqslant L \leqslant 1.4$) for several integral energies.

and

$$\lambda = \pi(L)B + \sigma(L)\ , \qquad \sigma = \epsilon L + \phi\ ,$$

$$\pi = \frac{\partial \lambda}{\partial B} = \beta L + \zeta\ , \qquad \beta = \frac{\partial^2 \lambda}{\partial L \partial B}\ . \tag{3}$$

Combining the expressions yields a general function for the mean lifetime within the volume element:

$$\tau(B, L, E) = \alpha BLE + \beta BL + \gamma LE + \delta BE + \epsilon L + \zeta B + \eta E + \phi\ . \tag{4}$$

The coefficients of the variables $B$, $L$, and $E$ form a matrix and are found for a particular volume element by successively linearizing all the derivatives of $\tau$. For those intermediate volume elements for

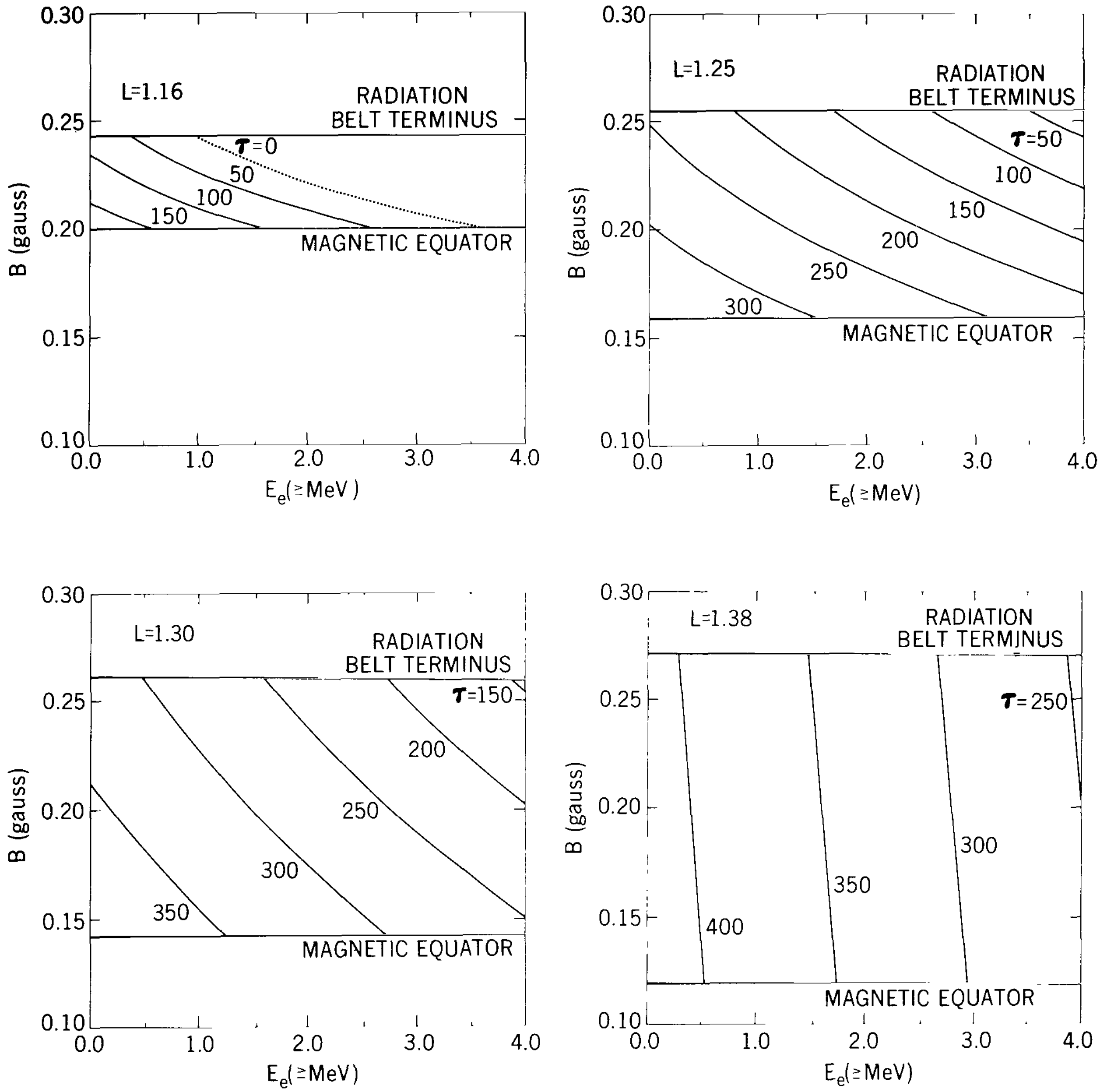


Figure 4—*BE* cross sections of the $\tau$ domain in region I $(1.15 \leqslant L \leqslant 1.4)$ at several $L$ values.

which coefficients cannot be determined due to sparse or insufficient data points, the known coefficient values from adjacent bracketing volume elements are linearly extrapolated, so as to match all slopes at the respective boundaries. Thus, a continuous functional relationship between the decay lifetime $\tau$ and its variables $B$, $L$, and $E$ is generated for the inner zone. Table 1 gives the values of the 30 sets of coefficients in the respective $L$ ranges. In Table 2 the predicted and measured counting rates of channels 1 and 2 are compared at selected $L$ values, for the period from January 1964 to December 1964.

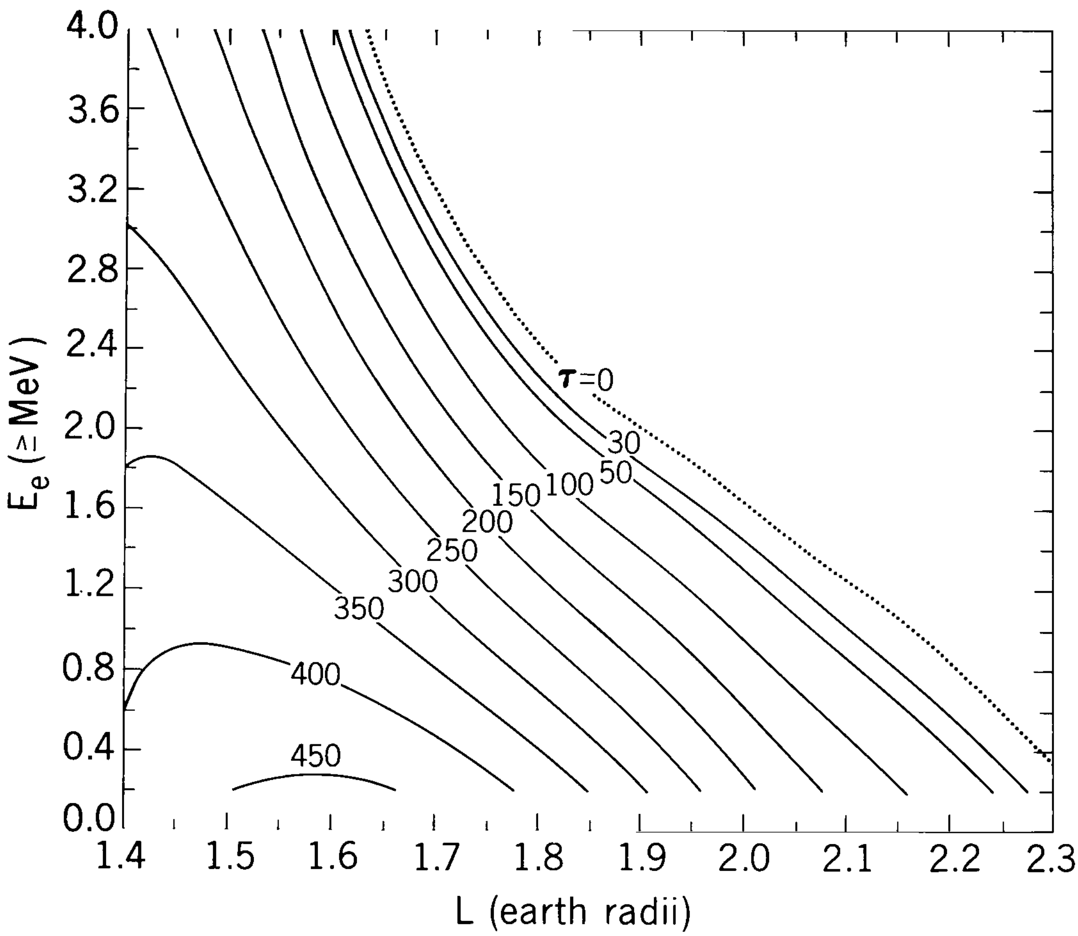


Figure 5—Decay lifetimes in region II ($1.4 \leqslant L \leqslant 2.3$) for integral energies above 0.2 MeV.

Table 2—Comparison of measured and predicted counting rates, January 1964-December 1964.

| $L$ | CPS ($E \geqslant .28$ MeV) | | % Difference | CPS ($E \geqslant 1.2$ MeV) | | % Difference |
|---|---|---|---|---|---|---|
| | Measured | Predicted | | Measured | Predicted | |
| 1.2 | 256 | 261 | ~2.0 | 226 | 229 | ~1.3 |
| 1.4 | 416 | 413 | ~0.7 | 372 | 375 | ~0.8 |
| 1.6 | 320 | 450 | ~40.6 | 302 | 349 | ~15.6 |
| 1.8 | 251 | 371 | ~47.8 | – | – | – |

Table 1—Coefficients of the lifetime function.

| Volume Element | $L$-Range | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ | $\epsilon$ | $\zeta$ | $\eta$ | $\phi$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.15 –1.16 | 6714.00 | 24830.00 | -1236.00 | -8529.46 | -4439.40 | -31067.70 | 1532.88 | 5778.45 |
| 2 | 1.16 –1.17 | 6322.00 | 19470.00 | -1150.00 | -8074.70 | -2174.50 | -24849.90 | 1433.12 | 3151.15 |
| 3 | 1.17 –1.18 | 8323.00 | 15000.00 | -1579.00 | -10415.91 | -1500.00 | -19620.00 | 1935.05 | 2362.00 |
| 4 | 1.18 –1.20 | 6584.50 | 12080.00 | -1176.50 | -8364.48 | -963.30 | -16174.40 | 1460.10 | 1729.36 |
| 5 | 1.20 –1.25 | 4203.60 | 11854.00 | -776.20 | -5507.40 | -1070.74 | -15903.20 | 979.74 | 1858.29 |
| 6 | 1.25 –1.28 | 3520.67 | 10383.30 | -657.13 | -4653.73 | -878.33 | -14064.80 | 830.91 | 1617.78 |
| 7 | 1.28 –1.30 | 2770.00 | 9020.00 | -520.80 | -3692.88 | -863.25 | -12319.80 | 656.40 | 1598.48 |
| 8 | 1.30 –1.32 | 1812.00 | 8030.00 | -406.30 | -2447.48 | -820.80 | -11032.80 | 507.55 | 1543.29 |
| 9 | 1.32 –1.34 | 1485.50 | 7045.00 | -341.70 | -2016.50 | -506.20 | -9732.60 | 422.28 | 1128.02 |
| 10 | 1.34 –1.38 | 578.00 | 5634.15 | -139.25 | -800.45 | -484.33 | -7842.06 | 151.00 | 1098.71 |
| 11 | 1.38 –1.40 | 140.50 | 3346.70 | -18.00 | -196.70 | -216.95 | -4685.38 | -16.33 | 729.73 |
| 12 | 1.40 –1.425 | 0 | 0 | -258.88 | 0 | 560.00 | 0 | 320.90 | -358.00 |
| 13 | 1.425–1.45 | 0 | 0 | -292.00 | 0 | 400.00 | 0 | 368.10 | -130.00 |
| 14 | 1.45 –1.475 | 0 | 0 | -276.00 | 0 | 320.00 | 0 | 344.90 | -14.00 |
| 15 | 1.475–1.51 | 0 | 0 | -297.14 | 0 | 200.00 | 0 | 376.09 | 163.00 |
| 16 | 1.51 –1.55 | 0 | 0 | -337.75 | 0 | 175.00 | 0 | 437.40 | 200.75 |
| 17 | 1.55 –1.60 | 0 | 0 | -422.22 | 0 | 160.00 | 0 | 568.33 | 224.00 |
| 18 | 1.60 –1.625 | 0 | 0 | -425.20 | 0 | 40.00 | 0 | 573.10 | 416.00 |
| 19 | 1.625–1.65 | 0 | 0 | -419.32 | 0 | -80.00 | 0 | 563.55 | 611.00 |
| 20 | 1.65 –1.70 | 0 | 0 | -358.34 | 0 | -220.00 | 0 | 462.93 | 842.00 |
| 21 | 1.70 –1.75 | 0 | 0 | -321.38 | 0 | -400.00 | 0 | 400.10 | 1148.00 |
| 22 | 1.75 –1.775 | 0 | 0 | -241.24 | 0 | -520.00 | 0 | 259.85 | 1358.00 |
| 23 | 1.775–1.82 | 0 | 0 | -147.78 | 0 | -644.44 | 0 | 93.96 | 1578.89 |
| 24 | 1.82 –1.85 | 0 | 0 | 0 | 0 | -766.67 | 0 | -175.00 | 1801.33 |
| 25 | 1.85 –1.87 | 0 | 0 | 75.00 | 0 | -850.00 | 0 | -313.75 | 1955.50 |
| 26 | 1.87 –1.95 | 0 | 0 | 198.41 | 0 | -962.50 | 0 | -544.53 | 2165.88 |
| 27 | 1.95 –2.00 | 0 | 0 | 222.60 | 0 | -980.00 | 0 | -591.70 | 2200.00 |
| 28 | 2.00 –2.05 | 0 | 0 | 217.76 | 0 | -900.00 | 0 | -582.30 | 2040.00 |
| 29 | 2.05 –2.10 | 0 | 0 | 212.18 | 0 | -740.00 | 0 | -570.86 | 1710.00 |
| 30 | 2.10 –2.30 | 0 | 0 | 69.28 | 0 | -600.00 | 0 | -270.49 | 1418.00 |

## CONCLUSIONS

When the model presented in this treatment is used, the following should be considered:

(1) Decay lifetimes should not be extrapolated backward too close to the epoch of the nuclear event because the initial decay (first few weeks) is considerably faster than at the later times considered in the present analysis.

(2) The estimated maximum value of the error for the calculated $\tau$ is about 2 percent at intermediate $L$ values ($1.2 \lesssim L \lessim 1.5$). At higher $L$ values ($L \gtrsim 1.6$) and at low $L$ values ($L < 1.2$), the error increases to about 30 percent on the average.

(3) The functional dependence of $\tau$ on energy has been derived through use of integral energy channels and may differ from decay constants obtained from differential energy measurements.

(4) At low energies ($E_e \lesssim 0.20$ MeV), the validity of the energy dependence of $\tau$ becomes marginal. There is evidence that electrons of these energies do not manifest a decay (Pfitzer, 1968; Pfitzer and Winckler, 1968) but that they are mainly part of the natural component of the radiation belt. At the higher integral energies, it is felt that the treatment should not be extrapolated beyond $E_e \geqslant 5$ MeV.

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