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Title: Average Beta and Gamma Decay Energies of the Fission Products

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One method of predicting the decay-heat is the "Summation Method" in which the power produced by decay of each fission product at time t after shut-down is calculated. The reactor shut-down power produced at time t is then obtained by summing over all of the fission products. An accurate determination of the average beta and gamma decay energies is essential for the success of this method.

Out of approximately 850 fission products, there are only about 150 whose beta and gamma decay energies have been measured. The rest were predicted by a fitting formula in which the ratio of decay energy to beta-decay Q value is taken as a linear sum of terms in mass number, charge number, and nuclear pairing energy; the coefficients were determined by a least-squares fit to known data.

Instead of fitting, the average beta and gamma decay energies can be calculated theoretically. Nuclear models, such as the shell model and the collective model, can predict the first few low-lying excited states quite well on the average. On the other hand, the statistical

model can be used for higher excited states, which we can approximate by assuming that the states form a continuum.

The probability of beta decay can be taken as proportional to $E^5\rho$, where E is the beta end-point energy and ρ is the angular-momentum-dependent level density. If the parent nuclide's ground state spin and parity are known, then for allowed beta transitions ($\Delta J = 0, \pm 1$, no parity change) in the continuum, the average beta end-point energy and level density (at that end-point energy) for each ΔJ can be calculated, In the continuum, first forbidden transitions ($\Delta J = 0, \pm 1, \pm 2$, yes parity change) are negligible compare to allowed transitions. However, for the discrete region (low-lying states), first forbidden transitions may be competitive, and they must be taken into consideration when necessary. By the above procedure, a fictitious beta decay level diagram for each nuclide was constructed and its average beta and gamma decay energies per disintegration could be computed.

One hundred and thirty-six nuclei, which have experimental measurements, were subjected to this theoretical calculation. When calculated values ($E_\beta + E_\gamma$) were compared to experimental values for those nuclei, the differences between calculated $E_\beta + E_\gamma$ and experimental $E_\beta + E_\gamma$ divided by their Q values are found to be a normal distribution with one standard deviation (σ) of 0.1567 (for $E_\beta + E_\gamma$, then $\sigma = 0.1567Q$). By this method, beta and gamma decay energies and their uncertainties can therefore be determined

without bias and fairly precisely.

Two summation method calculations were performed using ROPEY, a summation method code which was developed and used at Oregon State University. Treating other input parameters, namely, half-lives, branching ratios, and independent nuclear fission product yields as fixed, decay-heat calculated by using results of this study ($E_\beta + E_\gamma$) compared better than a calculation using the existing Evaluated Nuclear Data File B-IV (ENDF/B-IV) did with the American Nuclear Society (ANS) Decay-Heat Standard for the decay time between 1 and 60 seconds. Between 60 and 10,000 seconds of decay time, experimental data dominate the results, which are virtually identical.

Average Beta and Gamma Decay Energies of the Fission Products

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AVERAGE BETA AND GAMMA DECAY ENERGIES OF THE FISSION PRODUCTS

I. INTRODUCTION

I.1 Decay-Heat of a Fission Reactor

Hahn and Strassmann[1] were the first to establish that uranium, when bombarded with neutrons, splits into lighter elements with about half the atomic number of uranium. The phenomenon of a nucleus undergoing a division into two more or less equal fragments, either spontaneously or induced by some projectile, is termed binary fission. Less frequently, division into three fragments has also been observed; this is called ternary fission. It is easy to see, from the binding-energy versus mass-number curve shown in Figure 1-1, why fission is an energetically favorable process for heavy nuclei. The binding energy per nucleon in ^{238}U, for instance, is about 7.5 MeV, while it is about 8.4 MeV in the neighborhood of $A = 238/2 = 119$. Thus if a uranium nucleus divides into two lighter nuclei, each with about half the uranium mass, there is a gain in the binding energy of the system of approximately 0.9 MeV per nucleon which implies that a more stable configuration is formed when uranium fissions.

About two to four neutrons are emitted from the fragments within a time of 10^{-15} to 10^{-18} seconds after the division takes place. These prompt neutrons are emitted with a continuous distribution of energies, and on the average, each neutron carries away about two MeV

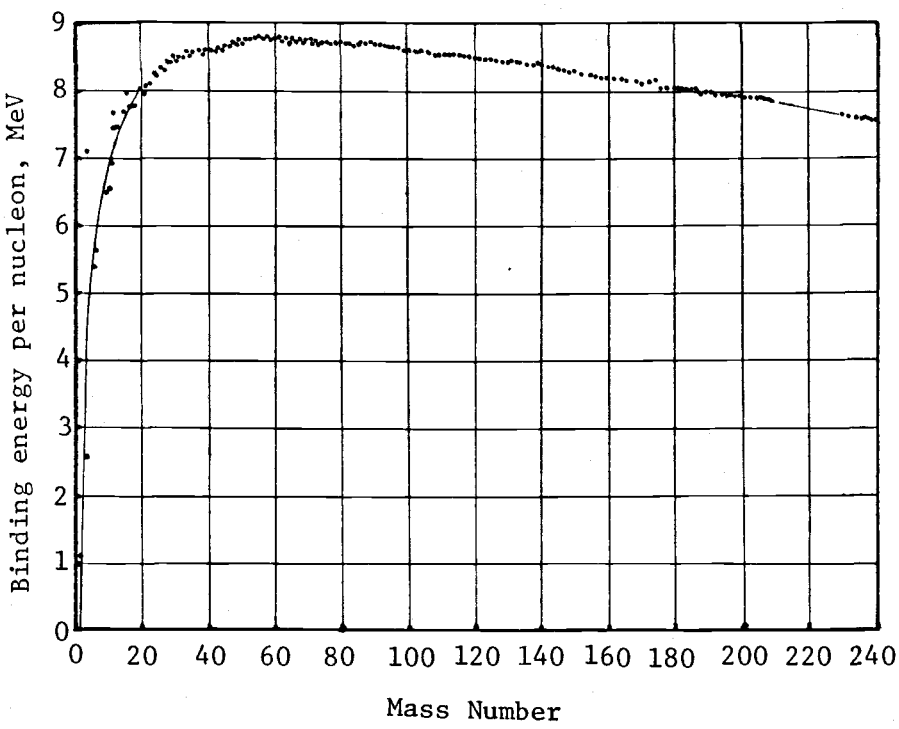

FIGURE 1-1 Binding energy per nucleon as a function of mass number.

of energy. In addition, of course, it costs energy for these neutrons to "evaporate" from the fragments - about eight MeV for each neutron. When the fragment-excitation energy has been reduced below the neutron-emission threshold, the fragments de-excite by γ-emission ($<10^{-11}$ seconds) to reach their ground state. These secondary fragments (also called primary fission products) are far removed from the β-stability line because their charges have not been readjusted. The primary products thus undergo the slow process of β-decay ($\sim 10^{-2}$ seconds or more), forming stable end products.[2] Occasionally it may happen that certain β-decay paths lead to a level that is neutron unstable, causing the emission of delayed neutrons.

Half-lives in beta decays can range from less than a tenth of a second to 10^{16} years.[3] Therefore, the decay of fission fragments continues even after a reactor is shut down. This decay energy (called decay-heat), emitted in the form of β- and γ-rays, provides a continuing source of heat (six to seven percent of the operating power at shut-down) that must be removed following shut-down. If decay-heat can not be removed, for example Emergency Core Cooling System (ECCS) was not sufficient or operable during a Loss of Coolant Accident (LOCA), the consequences would be very serious - core meltdown. Therefore, an accurate evaluation of decay-heat is necessary in order to install an adequate and sufficient ECCS. On the other hand, if the decay-heat is known accurately, an accurate assessment of the consequences of a LOCA,

in the unlikely event the ECCS fails, can be made.

Still, decay-heat also plays an important part at the end of the fuel cycle: namely, the design of storage pools, shipping containers, and reprocessing facilities for the spent fuels.

I.2 Decay-Heat Summation Methods

The basic idea of decay-heat summation techniques is simply to add the contributions of all the individual decaying fission-product isotopes to arrive at the total decay power. The following paragraphs define the functions which are of interest in decay-heat discussions.

If a burst of fission occurs in a reactor at time $t = 0$, then the number of atoms of each fission product can be calculated[4] as a function of time after the fission burst. Let $N_i(t)$ be the number of atoms per fission of the ith fission product present at time t after the burst where $1 \leq i \leq n$, and n is the number of fission products which contribute significantly to decay-heat. If λ_i is the decay constant (in sec^{-1}), and E_i is the average sensible energy of decay for the ith fission product (in MeV per decay), then reactor decay power per fission at time t after a fission is given (in MeV/sec/ fission) by:

$$H_o(t) = \sum_{i=1}^{n} \lambda_i N_i(t) E_i . \qquad (1.1)$$

If the reactor is operated at a steady power of P fissions/sec from time $t = -T$ to $t = 0$ and then shutdown, then for $t \geq 0$, reactor

shutdown power in MeV/sec shutdown power per fission/second operating power is given by (ignoring neutron capture effect)

$$H_1(t,T) = \int_{-T}^{o} H_o(t-t')dt'. \qquad (1.2)$$

Expressed in terms of parameters λ_i, E_i and $N_i(t)$, $H_1(t,T)$ function becomes

$$H_1(t,T) = \sum_{i=1}^{n} \lambda_i E_i \int_{-T}^{o} N_i(t-t')dt'. \qquad (1.3)$$

Summation calculations are somewhat complementary to experimental measurements of decay-heat. Due to the great variety of operating histories of reactors, experiments can not be performed for every imaginable situation; therefore, summation calculations of decay-heat have to be used in order to augment and enhance experimental determinations. The summation method of calculating decay-heat has also been a major tool in reconciling individual nuclide data with experimental decay-heat measurements for they can give detailed isotopic inventories and gamma spectra important in radiation and shielding applications.

I.3 Goal of this Dissertation

Theoretically, one would expect all summation method codes to give the same results because all these codes solve the same set of differential equations. But in the past, due to different data bases having been used, substantially different results were obtained. For example, due to one mistake in the branching ratio of ^{98}Zr, a great discrepancy[5] was found between results calculated

at Los Alamos National Laboratory[6] and Oregon State University.[7] When this was corrected, the discrepancy disappeared. Therefore, an accurate nuclear data library is essential for the effectiveness and acceptance of the summation prediction. Evaluated Nuclear Data File B-IV (ENDF/B-IV) is such a library.[8]

There are basically four input parameters to the summation method codes, namely, half-lives, branching ratios, independent fission product yields, and average beta and gamma decay energies. In their studies of uncertainties in fission-product decay-heat calculations, Schmittroth and Schenter[9] concluded that the main sources of uncertainty in decay-heat summation calculations are due to fission yields and decay energies; and for the thermal fission of ^{235}U, where fission yields have been extensively studied, decay energies are the major source of decay-heat error, especially for the very short decay times (less than 100 seconds).

An independent evaluation of uncertainties in decay-heat was also carried out at Oregon State University,[5,10,11] similar conclusions were obtained. Since uncertainties in half-lives and branching ratios are small enough,[5,51] they can be neglected. Bjerke et al[5] considered four sources of uncertainty, namely, energy per fission; fission-product yields; fission-product-decay energies - uncorrelated (random error predicted by the model - Equation 1.4); and fission-product-decay energies - correlated (error from a bias in the model which systematically predicted

energies too high or too low - Equation 1.4). For a reference case of ^{235}U thermal fission, at constant power for 35,000 hours, without depletion or neutron capture in fission products, decay-energy uncertainties (correlated and uncorrelated, see Figure 1-2) are clearly the major sources of error, especially for decay times less than about 100 seconds. The uncertainties (one sigma, σ) are expressed as percent of decay power. For longer decay times, experimental values dominate and have smaller uncertainties which cause the dip in correlated uncertainty (curve D of Figure 1-2). Since decay-energy uncertainty is determined to be the dominant factor in total decay-heat uncertainty, it seems that improvements in the estimated decay energies are worth examining.

Due to lack of experimental values, the majority of the average beta and gamma decay energies listed in ENDF/B-IV were estimated from systematics. The explicit form used to estimate average beta and gamma decay energies for ENDF/B-IV was a linear function of the mass number, A; the neutron excess, N-Z; and the nuclear pairing energy, P; and represents the decay energy as fraction of the Q value:

$$\bar{E}_\theta = Q\,[a_\theta + b_\theta A + c_\theta (N-Z) + d_\theta P],^{(9)} \qquad (1.4)$$

where θ denotes either beta or gamma and the coefficients were determined by a least-squares fit to the known data.

The goal of this thesis is to develop another method of estimating beta and gamma decay energies. Beta decay theory and

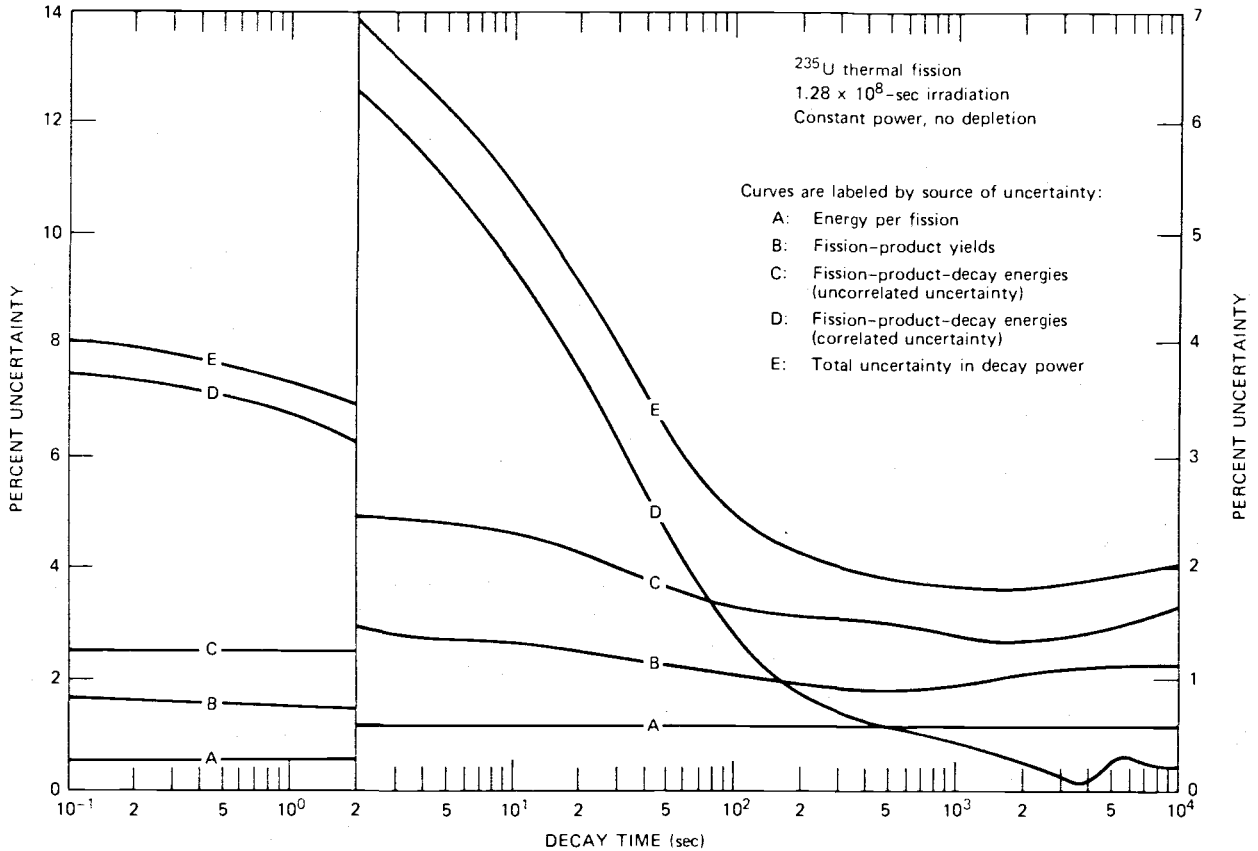

FIGURE 1-2 Uncertainties in summation calculations of decay power (from reference 5).

nuclear models can be used to construct fictitious beta decay diagrams; and from these diagrams, average beta and gamma decay energies per disintegration can be calculated.

II. BETA DECAY THEORY

II.1 Introduction

When the fission fragments are formed, they are excessively "neutron-rich", that is, they contain too many neutrons for stability. All neutron-rich nuclides will decay by beta (negatron) emission along their isobar lines toward the bottom of the mass parabola.[12] The beta decay process is characterized phenomenologically by the emission of an electron directly from a nucleus. Of course, there are electron captures, positron emissions, and delayed neutron emissions (important for reactor control), but they are not important for the de-excitation of fission fragments.

II.2 Beta Decay Q Values

For electron decay, conservation of energy requires

$$M_P c^2 = M_D c^2 + T_{e^-} + T_{\bar{\nu}}, \tag{2.1}$$

where M_P = atomic mass of the parent nuclide,

M_D = atomic mass of the daughter nuclide,

T_{e^-} = kinetic energy of the electron,

$T_{\bar{\nu}}$ = kinetic energy of the antineutrino,

and the recoil kinetic energy of the daughter nuclide as well as atomic electron binding energy differences are negligible. The corresponding definition of the beta decay Q values is

$$Q = (M_P - M_D)c^2 , \tag{2.2}$$

and

$$Q = T_{e^-} + T_{\bar{\nu}} = T_{e^-}(\text{max.}), \qquad (2.3)$$

which indicate Q is the total energy available for beta decay. Equations (2.1) and (2.3) are good for beta decay between ground states of the parent and daughter nuclei. If instead of decaying to the ground state of the daughter nuclide, but to one of its excited states, then there will be an extra term to be added to Equations (2.1) and (2.3), namely gamma energy. Of course, Equation (2.2) still holds.

II.3 ft Values

A striking feature of nuclear beta decay is the great variation found in the half-lives. They range from less than a tenth of a second to 10^{16} years. The causes are:[3]

1). The amount of angular momentum carried off by the electron-antineutrino pair (that is, by the angular momentum change of the nucleus), and also on whether or not the parity of the nucleus changes in the transition (bases for selection rules). The transition probability is determined by the amplitude of the electron and antineutrino wave function at the nucleus. This is largest (in turn, shortest half-life) if the two particles carry off no angular momentum - at least no orbital angular momentum - and if there is no parity change.

2). The second cause of the variation of beta decay half-lives

is the available beta decay energy. The probability of decay depends on the phase space available for the leptons. This space increases very rapidly with the available energy. In addition, there is a significant effect of the nuclear coulomb field on the wave function of the emitted electron. As a result, the beta decay half-life will depend on the atomic number of the nucleus involved. The energy and coulomb effect are not, of course, directly connected with the details of the nuclear states. Therefore we should like to separate these effects out in order to study explicitly how the beta decay transition probability depends on the wave functions of the nuclear states involved. This can be accomplished by characterizing a beta decay, not by its half-life but rather by a so-called comparative half-life ft where f includes the effect of the energy and coulomb field on the half-life t. Thus two decays with the same nuclear structure but different energies and different nuclear charge will have different half-lives t but should have the same ft value. The values of f for allowed transitions can be read from a set of graphs prepared by Feenberg and Trigg.[13] A table listing of $\log_{10}$ft for allowed and first forbidden transitions is also available.[14] A rapid method of calculating the $\log_{10}$ft values for allowed transitions

can be found in reference (3). For T_{e^-}(max.) >1 MeV, f is roughly proportional to the fifth power of T_{e^-}(max.).[15]

II.4 Selection Rules

From conservation of angular momentum and parity, we can deduce how J and π must change in the nucleus. In a Fermi transition[16] the only angular momentum carried off by the electron and antineutrino is their orbital angular momentum ℓ (intrinsic spin of electron and antineutrino are antiparallel), so the angular momentum of the parent and daughter nuclei, J_P and J_D, respectively, must satisfy the vector addition

$$J_D = J_P + \ell. \tag{2.4}$$

In a Gamow-Teller transition,[17] the electron and antineutrino carry off an additional spin angular momentum of one unit (intrinsic spin of electron and antineutrino are parallel), whence

$$J_D = J_P + \ell + 1. \tag{2.5}$$

Conservation of parity requires that the product of the parities of the terms in the final wave function - the wave function of the electron, antineutrino, and daughter nucleus - be the same as the parity of the initial (Parent nucleus) wave function. Since the parity of the electron-antineutrino wave function is $(-1)^{\ell}$, this requires

$$\pi_P = \pi_D(-1)^{\ell}. \tag{2.6}$$

Decays with $\ell = 0$ are called allowed, with $\ell = 1$ first forbidden,

$\ell = 2$ second forbidden, etc.

Only allowed and first forbidden transitions will be considered here, selection rules are listed below.

TABLE 2-1 Beta decay selection rules for allowed and first forbidden transitions (from reference 18).

Class of transition	ℓ	Parity change	$\Delta J = J_D - J_P$	
			Fermi	Gamow-Teller
Allowed	0	No	0	0,±1
First forbidden	1	yes	0,±1	0,±1,±2

III. NUCLEAR MODELS

III.1 Introduction

One of the main objectives of the study of nuclear physics is understanding the structure of nuclei. Generally, nuclear structure theories are formulated in terms of some models which can predict various observable properties of the nuclides in a systematic way and without prohibitively lengthy calculations. Obviously, nucleus is a complicated system and there is no single model that can explain all the nuclear properties and structural characteristics satisfactorily; in other words, many models are needed. Out of the many existing models, only two models, namely, the deformed shell model and the collective model, are relevant to this study. They will be discussed briefly here.

III.2 The Deformed Shell Model

The Nilsson Model[19] is essentially a deformed shell model, derived by applying a modified shell-model approach to the independent particle motion (therefore, appropriate for odd-A nuclei) of nucleons within an average axially-symmetric deformed nuclear potential. The latter is assumed to include a spin-orbit term and to have a diffuse surface; for simplicity, Nilsson used an anisotropic harmonic-oscillator potential as a basis, but introduced a correction term to reduce the otherwise too pronounced surface

diffuseness. The treatment by Nilsson is too lengthy to reproduce here, but good references are plentiful.[2,20,21]

Results from Nilsson model which are useful (applicable to spherical nuclei) in this study are outlined below.

$$H = H_o + \chi\hbar\omega_o R,^{(22)} \tag{3.1}$$

$$H_o = (-\hbar^2/2m)\nabla^2 + (m/2)\omega_o^2 r^2, \tag{3.2}$$

where H_o = the usual harmonic-oscillator Hamiltonian,

$\chi = 0.05$

$$\hbar\omega_o = 41/(A^{1/3}) \quad \text{(MeV)} \tag{3.3}$$

$R = \xi u - 2\vec{\ell}\cdot\vec{s} - \mu\ell^2$

$\xi \propto$ deformation parameter from sphericity,

$\vec{\ell}\cdot\vec{s}$ = the spin-orbit term

ℓ^2 = the correction term to reduce the otherwise too pronounced surface diffuseness,

N = 0, 1, 2	$\mu = 0.00$
N = 3	$\mu = 0.35$
N = 4, 5, 6	$\mu = 0.45$
N = 7	$\mu = 0.40$

N = the quantum number which characterizes the various harmonic-oscillator shells.

For spherical ($\xi = 0$) nuclei, the Nilsson level-scheme becomes as shown in Figure 3-1.

In this study, only relative energy values are used, i.e. energy differences between specific levels and ground state

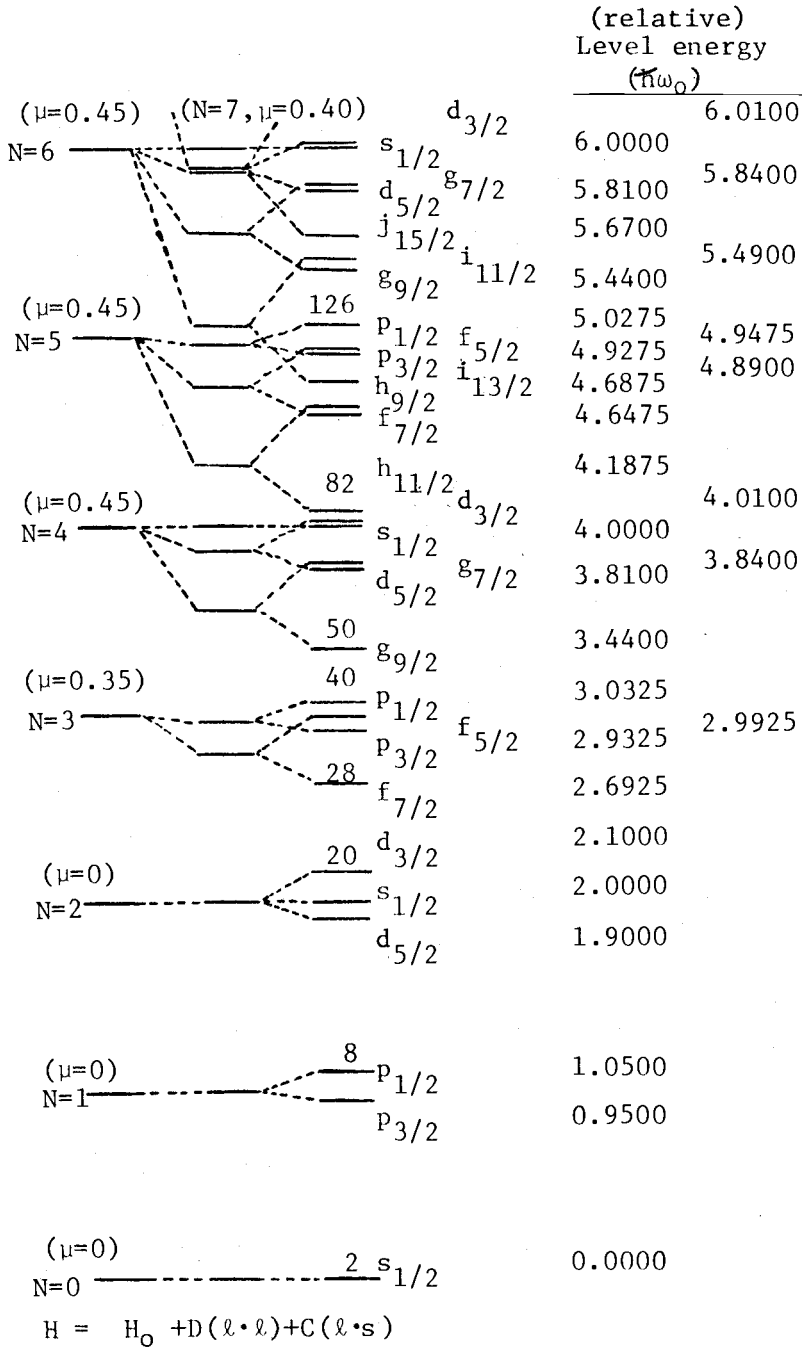

FIGURE 3-1 Level diagram derived from Nilsson's spherical Hamiltonian (from reference 21).

($N = 0$, $s_{1/2}$), or energy differences between two levels. In other words, the absolute energy of each level is not important. Therefore, the ground state energy is made equal to zero instead of $(3/2)\hbar\omega_o$ (zero point energy). These energy difference values are listed in the last column of Figure 3-1.

III.3 The Collective Model

Many features of nuclei indicate that nuclear motion does not consist only of simple single-particle excitations as might be suggested by the shell model. Instead there are several typical effects[20] which imply a collective motion, that is a motion where many nucleons move coherently with well-defined phases.

A spherical (or nearly spherical) nucleus, in the simplest model, may be assumed to be a charged liquid drop, its excitation modes arising from small oscillations of harmonic type about the equilibrium spherical shape. The motion is that of a surface wave going around the nucleus carrying a certain amount of mass and producing a pressure at the bulge because of the centrifugal force. This is counteracted by the surface tension, which represents the spring force. The lowest quantum of such collective excitation, called a phonon, has a quadrupole type of deformation and carries an angular momentum of two units and positive parity. In even-even nuclei with small deformations, one therefore expects to find a $J = 2^+$ first excited state which is the one-phonon vibrational state.

Higher excited states can be formed by two or more quadrupole phonons or by octupole vibrations, the latter having distortions expressible through spherical harmonic functions of third order and carrying angular momenta of three units with negative parity.

Figure 3-2 shows schematically the predicted energy-level diagram of those even-even nuclei that are expected to display vibrational-type spectra. A considerable amount of experimental information verifies this scheme, at least in part.[23] And Figures 3-3 and 3-4 show the lowest-energy 2^+ and lowest-energy 3^- states in even-even nuclei.

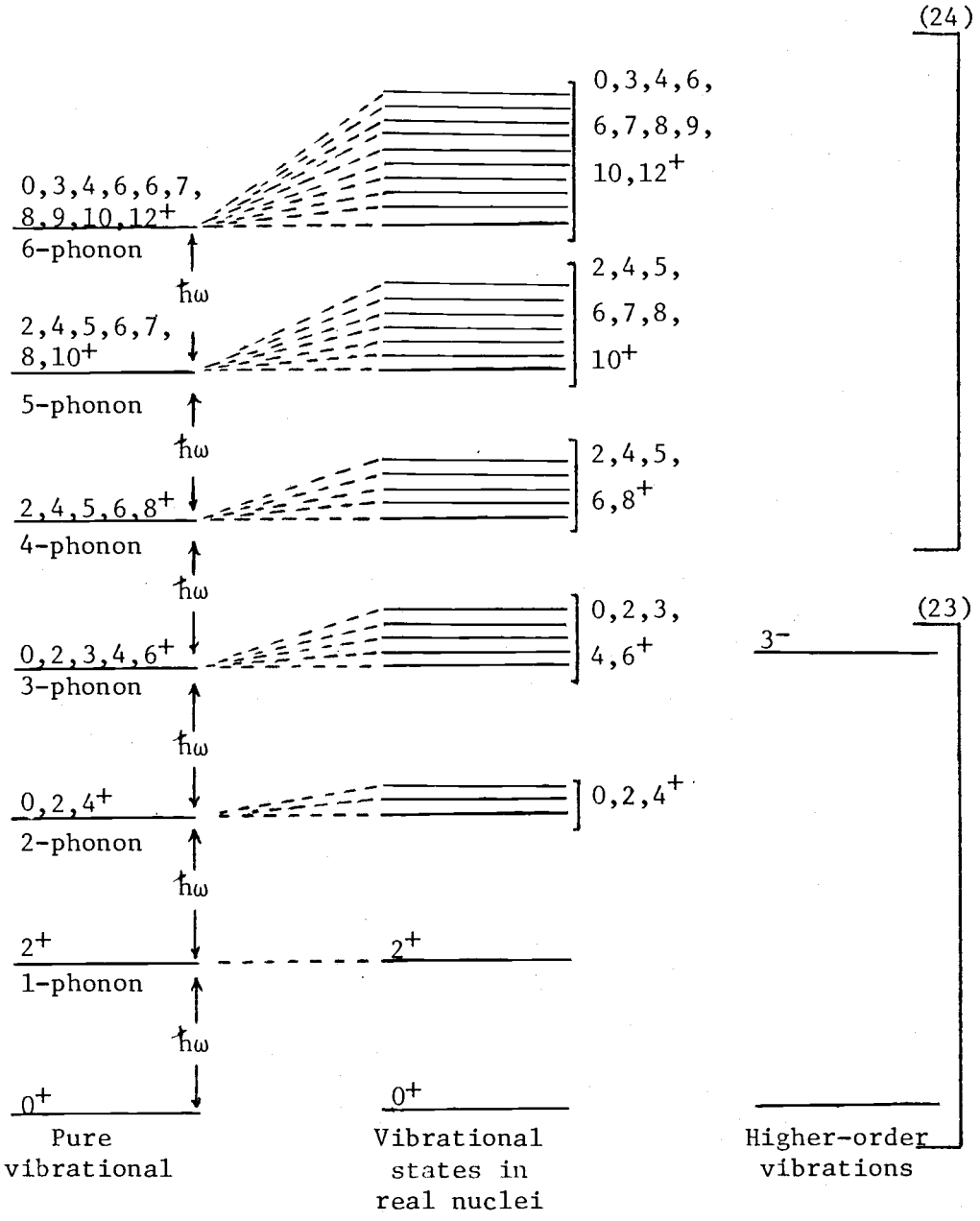

FIGURE 3-2 Schematic vibrational energy-level diagram of even-even nuclei (from references 23 and 24).

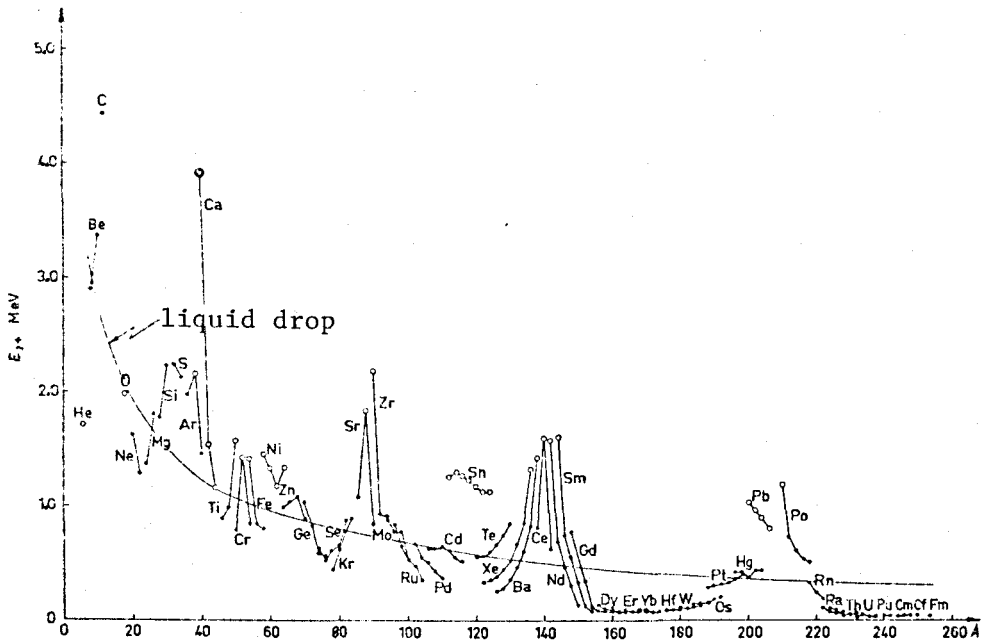

FIGURE 3-3 The energy E_{2^+} ($\hbar\omega$ of Figure 3-2) of the first excited 2^+ states in even-even nuclei. Those large fluctuations in energy is associated with the nuclear shell structure. Lines labeled "liquid drop" are energies expected if the nucleus vibrated like a classical liquid drop; they have been multiplied by an arbitrary constant to obtain the best fit to the data (from reference 25).

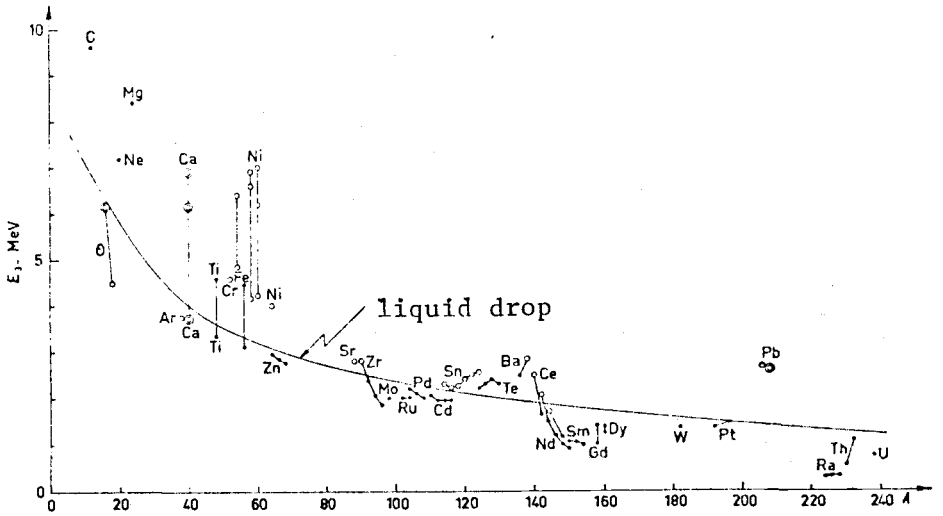

FIGURE 3-4 The energy $E3^-$ of the 3^- collective vibrational states in even-even nuclei. Lines labeled "liquid drop" are energies expected if the nucleus vibrated like a classical liquid drop; they have been multiplied by an arbitrary constant (twice as large for the 3^- as for 2^+) to obtain the best fit to data (from reference 25).

IV. NUCLEAR LEVEL DENSITIES

IV.1 Introduction

The levels of a nucleus can be divided into two energy regions, namely the low energy and high energy excitations. This division arises naturally from the different approaches employed for their analysis: the spectroscopical approach for the low energy levels and the statistical approach for the high energy levels. The low-lying nuclear excited levels are small in number, well separated, and rather simple in structure. With increasing excitation energy, the spacing between the levels is progressively reduced and the nature of the excitations become very complicated. The existence of such complex levels is beautifully illustrated by the neutron-capture resonances.

Because of the complexities involved, the statistical approach which allows a more unified description of the average behavior at high excitation energy, is found to be most useful. The most relevant quantity describing the statistical nuclear properties is then the level density of the system, expressed as a function of the various constants of motion, e.g. excitation energy, number of particles, angular momentum, parity, isospin, etc.

IV.2 Theoretical Considerations

The level-density formula adopted is essentially that of Bethe:[26,27]

$$\rho(U,J) = \frac{\sqrt{\pi}}{12} \frac{\exp(2\sqrt{aU})}{a^{1/4}U^{5/4}} \frac{(2J+1)\exp[-J(J+1)/2\sigma^2]}{2\sqrt{2\pi}\sigma^3}. \tag{4.1}$$

$\rho(U,J)$ is the density (in Mev^{-1}) of levels of given angular momentum J (both parities are included, and for either parity, an equal probability assumption is valid[28,29]) at an excitation energy U. The observable level density is

$$\rho(U) = \sum_J \rho(U,J) = \frac{\sqrt{\pi}}{12} \frac{\exp(2\sqrt{aU})}{a^{1/4}U^{5/4}} \frac{1}{\sqrt{2\pi}\sigma} . \tag{4.2}$$

This is not to be confused with the "total" level density

$$\Omega(U) = \sum_J (2J+1)\rho(U,J) = \frac{\sqrt{\pi}}{12} \frac{\exp(2\sqrt{aU})}{a^{1/4}U^{5/4}} , \tag{4.3}$$

which includes levels degenerate in M, the magnetic quantum number (there are 2J+1 of these for every value of J). a is defined as the "level density parameter". The spin-dependence parameter is given by

$$\sigma = g\langle m^2\rangle\tau. \tag{4.4}$$

Here g is the sum of the neutron and proton single-particle level spacings, and is related to a by

$$a = (1/6)\pi^2 g. \tag{4.5}$$

τ is the thermodynamic temperature of the nucleus given by

$$\tau = \sqrt{U/a}, \tag{4.6}$$

and $\langle m^2\rangle$ is the mean-square magnetic quantum number for single particle states. Putting all this together, one obtains

$$\sigma^2 = 0.0137A^{5/3}\sqrt{U/a} \quad .^{(30)} \tag{4.7}$$

Hence σ varies as $U^{1/4}$, which is a rather slow variation.

IV.3 Determination of Parameters

We have two free parameters, a and U to fit the level-density formula to the neutron resonance data. If one thinks of U simply as the excitation energy, then the remaining parameter a could be fitted to match theoretical predictions with observed neutron resonance spacings. If this is done, there are systematic differences in the values of a for neigboring even-even, odd-A and odd-odd nuclei.[28] It was Newton[31] who first showed that these discrepancies could be removed by subtracting a "pairing energy" from the excitation energy to obtain U.

These odd-even effects are found also in nuclear masses and nucleon binding energies, and so it seems natural to use the pairing energies from a semi-empirical mass formula.[28] The free parameters of the semi-empirical mass formula were first adjusted to fit experimental masses of odd-odd nuclei (no pairing energy) not too near major closed shells. By the use of this "reference formula", masses can be calculated for all kinds of nuclei, and the differences between the computed and experimental masses will have systematic odd-even and shell effects. These differences are decomposed into two parts, one a function of Z, the other a function of N. Each part can be broken up further to separate the odd-even effects from the shell effects. The semi-empirical mass formula was obtained by considering a Fermi gas model of the nucleus, where the single-particle density of states was a smooth function of energy. In

reality, the single-particle levels in a real nucleus are discrete with large energy gaps between major shells. In other words, a correction term due to shell effect needs to be incorporated in semi-empirical mass formula in order to obtain better agreement with experimental results. This correction term is called shell correction. Methods of evaluation of S(Z) + S(N) can be found in references (32,33). Thus one gets pairing energies P(N) and P(Z), and shell corrections S(N) and S(Z), for neutrons and protons respectively. These are listed in Tables 4-1 and 4-2.

U is now defined by

$$U = E - P(N) - P(Z), \tag{4.8}$$

where E is the total excitation energy, while P(N) and P(Z) are zero for odd values of N or Z. The adopted formula (4.1) represents the level density of a gas of independent fermions. We should hardly expect nucleon-nucleon interactions to be negligible near the ground state. Equation (4.8) implies that we must expend some energy, P(N) + P(Z), to break up the nucleon pairs, before the protons and neutrons can be considered independent particles.

If the observed resonance spacing (D_{obs}) is known, then observed level density $\rho_{obs} = 1/D_{obs}$ and a can be calculated by using (4.1). But nuclei with observed resonance spacing are small in number; therefore a has to be obtained by other means (see next section).

TABLE 4-1 Pairing energies and shell corrections for protons.[28]

Z	P(Z) (Mev)	S(Z) (Mev)	Z	P(Z) (Mev)	S(Z) (Mev)
24	1.35	-14.71	48	1.36	-18.58
25	0.00	-15.53	49	0.00	-19.11
26	1.54	-16.37	50	1.19	-19.83
27	0.00	-17.36	51	0.00	-19.14
28	1.20	-18.52	52	1.14	-18.35
29	0.00	-18.44	53	0.00	-17.40
30	1.06	-18.19	54	1.12	-16.54
31	0.00	-17.68	55	0.00	-15.68
32	1.36	-17.09	56	1.58	-14.75
33	0.00	-16.65	57	0.00	-13.71
34	1.43	-16.66	58	1.17	-12.87
35	0.00	-16.59	59	0.00	-12.18
36	1.17	-16.35	60	1.18	-11.61
37	0.00	-16.18	61	0.00	-11.09
38	1.24	-16.41	62	1.22	-10.78
39	0.00	-16.60	63	0.00	-10.53
40	1.20	-16.54	64	.97	-10.41
41	0.00	-16.42	65	0.00	-10.21
42	1.28	-16.84	66	.92	-9.85
43	0.00	-17.22	67	0.00	-9.36
44	1.28	-17.42	68	.62	-8.97
45	0.00	-17.52	69	0.00	-8.56
46	1.35	-17.82	70	.68	-8.13
47	0.00	-18.19			

TABLE 4-2 Pairing energies and shell corrections for neutrons.[28]

Z	P(N) (Mev)	S(N) (Mev)	Z	P(N) (Mev)	S(N) (Mev)	Z	P(N) (Mev)	S(N) (Mev)
36	1.50	17.55	61	0.00	19.22	85	0.00	11.18
37	0.00	17.98	62	1.25	19.51	86	.92	11.70
38	1.50	18.33	63	0.00	19.73	87	0.00	12.22
39	0.00	18.56	64	1.14	19.91	88	.99	12.71
40	1.43	18.71	65	0.00	20.06	89	0.00	13.05
41	0.00	18.65	66	1.32	20.16	90	1.10	12.99
42	1.88	18.55	67	0.00	20.09	91	0.00	12.62
43	0.00	18.52	68	1.15	19.83	92	.92	12.11
44	1.47	18.34	69	0.00	19.41	93	0.00	11.66
45	0.00	18.01	70	1.24	19.06	94	.73	11.21
46	1.57	17.38	71	0.00	18.66	95	0.00	10.81
47	0.00	16.56	72	1.43	17.73	96	.70	10.38
48	1.46	15.62	73	0.00	17.03	97	0.00	10.03
49	0.00	14.38	74	1.09	16.44	98	.87	9.65
50	.93	12.88	75	0.00	16.00	99	0.00	9.38
51	0.00	13.24	76	1.20	15.33	100	.61	8.99
52	.72	13.71	77	0.00	14.49	101	0.00	8.62
53	0.00	14.40	78	1.04	13.42	102	.60	8.33
54	1.12	15.16	79	0.00	12.28	103	0.00	8.10
55	0.00	15.89	80	.70	11.14	104	.55	7.82
56	1.29	16.43	81	0.00	10.10	105	0.00	7.56
57	0.00	16.97	82	.85	9.09	106	.40	7.33
58	.94	17.59	83	0.00	10.00	107	0.00	7.15
59	0.00	18.08	84	.76	10.64	108	.73	6.83
60	1.24	18.72						

IV.4 Discussion of the Parameter a[28]

The Bethe free gas model[26,27] considers the nucleus to be a Fermi gas of free neutrons and protons confined to the nuclear volume, and gives

$$a/A = \text{constant}. \tag{4.9}$$

There is certainly an overall increase of a with A, although there are departures from this simple rule. There is no systematic difference left due to odd-even effects. Thus the pairing energies have fulfilled their intended function.

There are obvious shell effects present in a; there is a drop in a especially in the region of the double closed shell $Z = 82$, $N = 126$. The $N = 82$ and $N = 50$ shells produce the same effect (but not the $Z = 50$ shell). The Bethe model does not make provision for shell effects. The first attempt to deal with them was due to Newton,[31] but was not very satisfactory.

Cameron[34] was able to improve the situation. Since pairing energies derived from semi-empirical mass formula have been used to remove the differences due to odd-even effects, it seems natural to consider the use of shell corrections to remove the differences between nuclei near and far from closed shells. In Bethe's theory a/A is constant. We shall try to find a connection between a/A and S, the shell correction.

Figure 4-1 shows a plot of a/A vs. $S = S(N) + S(Z)$, the total shell correction in MeV. There is a clear distinction between

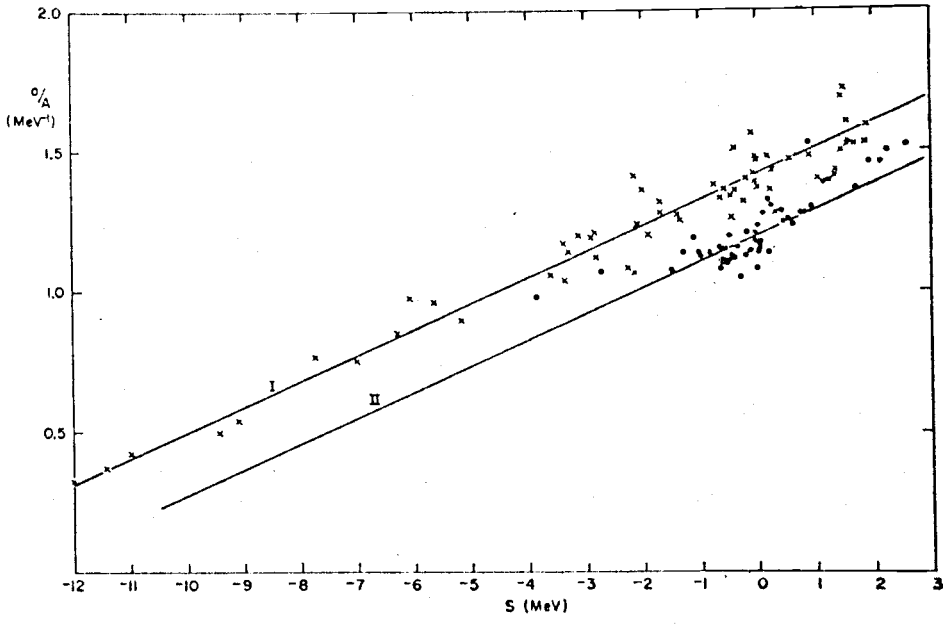

FIGURE 4-1 a/A vs. the total shell corrections. Crosses correspond to undeformed nuclei, dots to deformed nuclei (from reference 28).

deformed and undeformed nuclei.

For the undeformed nuclei we have a good linear correlation (line I of Figure 4-1)

$$a/A = 0.00917S + 0.142. \tag{4.10}$$

Thus, the simplest way to represent deformed nuclei is by a straight line parallel to I, namely line II:

$$a/A = 0.00917S + 0.120. \tag{4.11}$$

It is generally considered that nuclei will exhibit deformation whenever both N and Z are not near magic number. For our purpose we should consider the following to be regions of deformations:[28]

$$54 \leqq Z \leqq 78, \qquad 86 \leqq N \leqq 122,$$

$$86 \leqq Z \leqq 122, \qquad 130 \leqq N \leqq 182.$$

V. ALGORITHM DEVELOPMENT

V.1 Introduction

Physically we expect to find spherical nuclei near the magic numbers. Deformed nuclei occur if a sufficiently large number of neutrons and protons are outside closed shells so that the spherical shell structure can be destroyed and a new deformed shell structure can be set up. Indeed, the nuclear periodic table has three or possibly four regions where nuclei have been experimentally shown to be deformed, namely from A = 19 to 28, from 150 to 190, for A $\geqq$ 222, and possibly around A = 8.[20,35]

Only nuclei with mass numbers in the range between 66 and 172 are considered in this study; in this group, nuclei with A from 150 to 172 are in the deformed region. From Figure 5-1,[36,37] one can see that nuclei with A $\geqq$ 150, have very small yields. Therefore, very little error will be introduced into decay-heat calculations, even if one has the wrong decay energies for such nuclei from assuming those nuclei are spherical instead of deformed. However, one exception to the spherical assumption was made. Since Equation 4.11 is a linear correlation (see IV.4; Figure 4-1) for the deformed nuclei and is readily available in simple form, the parameter a/A was calculated using Equation 4.11 for a deformed nucleus rather than Equation 4.10.

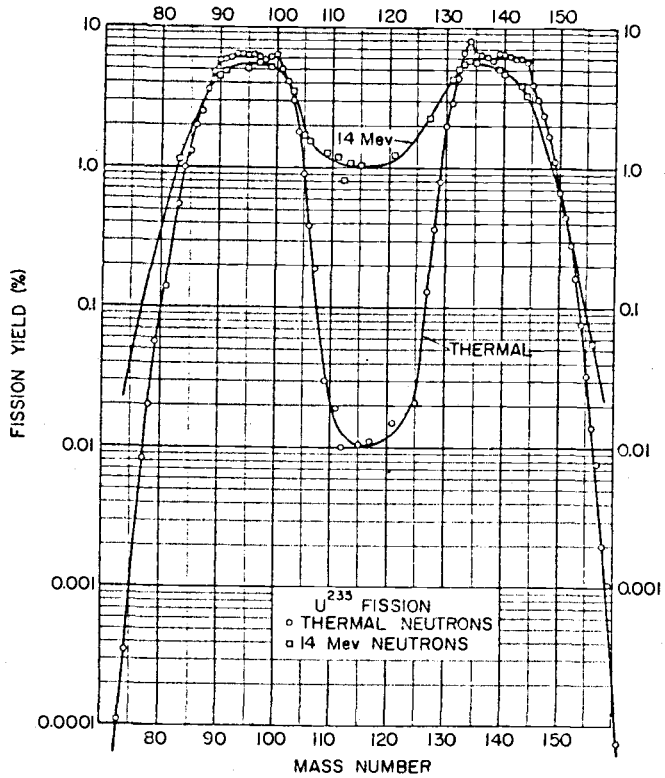

FIGURE 5-1 Post-neutron-emission mass distribution of ^{235}U fission (from references 36,37).

V.2 Ground State Spin and Parity

Nuclear ground state spin and parity (J^{π}) can be found or determined quite easily. In this study, experimental J^{π} will be used, if they can be found, i.e. from Nuclear Data Sheets[38] and Chart of Nuclides.[39] For other nuclei, some established rules can be used in order to determine their J^{π}. Rules are:

a). Due to pairing of nucleons, even-even nuclei have total ground state angular momentum and parity $J^{\pi} = 0^{+}$. There is no known exception to this rule.

b). An odd nucleus (odd Z or odd N) will have a total ground state angular momentum and parity equal to the half-integral angular momentum J and the parity $(-1)^{\ell}$ of the unpaired particle. Fig. 3-1 can be used to determine which shell the unpaired particle is in, and from this J and ℓ can be found. There are some exceptions to this rule because some of the levels inside a major closed shell are quite close in energy; due to pairing energy increasing with increasing ℓ, there is a tendency for pairs of particles to go into higher ℓ states.

c). For odd-odd nuclei, we can invoke Nordheim's rules.[40] If one defines Nordheim's number $N = j_p - \ell_p + j_n - \ell_n$, where j and ℓ are the resultant and orbital angular momentum of the unpaired nucleon respectively, then J of an odd-odd nuclide is given by

Strong rule: $N = 0$, $J = |j_n - j_p|$;

Weak rule: $N = \pm 1$, J is either $|j_n - j_p|$ or $j_n + j_p$.

$j = \ell \pm 1/2$ (1/2 is the intrinsic spin angular momentum); therefore, for $N = +1$, it implies $j_p = \ell_p + 1/2$ and $j_n = \ell_n + 1/2$. Similarly, for $N = -1$, it implies $j_p = \ell_p - 1/2$ and $j_n = \ell_n - 1/2$. In other words, both odd nucleons spin and orbital angular momenta are either both parallel ($N = +1$) or both antiparallel ($N = -1$), which makes $J = j_n + j_p$ the state of lowest energy.[2] However, the spacing between the states of $|j_n - j_p|$ and $j_n + j_p$ is fairly small so that reasonable perturbations might well alter the order. Since $J = j_n + j_p$ is the state of lowest energy; for odd-odd nuclei with $N = \pm 1$, their ground state angular momenta of $j_p + j_n$ will be assumed. Ground state parity is $(-1)^{\ell_p + \ell_n}$.

V.3 Metastable States

One can recognize the existence of a metastable state if one state of a nuclide has a large J relative to its lower energy states. Due to a large difference in J, transitions to lower states will be hindered. Hence, metastable states usually have measurable half-lives.

A metastable state can be treated as an extra parent nuclide

apart from the ground state. In other words, there will be two (maybe three, if branching occurs) distinct decays, namely, one from the usual ground state, and the other from the metastable state with its own spin, parity, and Q value. If E_M is the metastable state energy and Q_g is the beta decay Q value of its ground state, then the metastable state beta decay Q value should be the sum of E_M and Q_g.

Theoretically, metastable state spin, parity, and Q value can not be pinpointed easily. They are found mostly by experiments - spectroscopic determination[38,39] of nuclear energy levels. Thus, instead of guessing, metastable states without experimental spin, parity, and Q value will not be treated in this study. Their beta and gamma decay energies from references (8,10) will be used.

V.4 Beta Decay Q Value

Beta decay Q value is defined by Equation (2.2) which shows Q is equal to the atomic mass difference in Mev between parent and daughter nuclides. Accurate determination of Q values is a thesis topic by itself. Since Q values are not the main concern of this study, Q values obtained from references (41,42) will be utilized here.

V.5 Departure Energy (E_d) from Discrete Region to Continuum

It is necessary to determine what energy (E_d) to take for the onset of the continuum. In other words, at what energy can one ignore

the microscopic details of a nucleus and start considering its macroscopic properties by using the method of statistical averaging.

There is no definite departure energy that can be cited from literature. Therefore, one has to exercise one's judgement. In this study, departure energy is calculated from level density, since this indicates how densely are the levels populated. Departure energy which given "total" level density (Equation 4.3) of 30 levels/MeV seems to be a reasonable choice because of two initial considerations. Of course, this is confirmed later by the final results shown in Figure 7-5. The two initial considerations are:

1). Since the computer resources available are limited and there are a lot of nuclei under investigation, a lower level density value is more economical. The reason is that in the program which was adopted "total" level density $\Omega(U)$ is evaluated repeatedly for increments of 0.001 MeV in U until a specific U is found which gives the desired $\Omega(U)$, say 30 levels/MeV. For each nucleus, it requires many many such evaluations and many more evaluations are required, if $\Omega(U)$ is higher. (To conserve computer resources, a root finding technique should be used, but for this study, it is too late to make such a change).

2). Even though a lower "total" level density is desirable for reasons just given, it has to be realistic with respect to the continuum approximation. From the

discussions of the collective model, one can see, for some deformed nuclei (A from 150 to 190), the energies of their lowest-energy 2^+ states are of the order of 0.1 MeV which are comparable to the level spacings if "total" level density is 10 levels/MeV; which means level density of 10 levels/MeV is not realistic with respect to the continuum approximation. Accordingly, level density of 30 levels/MeV is chosen as the departure level density.

After U corresponding to the departure level density is obtained, the departure energy [= U + P(N) + P(Z)] can be found by using Equation (4.8). Even though 30 levels/MeV was used for departure level density for all nuclei, due to shell effects in the parameter a and the pairing energy, the departure energy is generally different between nuclei.

The departure energy taken as that energy where the "total" level density is only 20 levels/MeV has also been investigated; it gave slightly inferior final results.

V.6 Discrete States Region

In the region of discrete states, as the name implies, energy levels are discrete, therefore level configurations are governed by nuclear models. Also, discrete states can only be filled up to the departure energy. Therefore, the energy of the last discrete

state will be either equal to or less than departure energy.

V.6.1 Even-Even Nuclei

All even-even nuclei will have ground state $J^{\pi} = 0^{+}$, and their level configurations and level energies can be obtained according to the level diagram predicted by the collective model.

V.6.2 Odd-A Nuclei

For odd-A nuclei, ground state J^{π} are determined by the last unpaired nucleon. For example, for Z (or N) = 49 and from Figure 3-1, ground state $J^{\pi} = 9/2$ (or $g_{9/2}+$). Again, the level configurations and level energies are determined precisely by the level diagram derived from Nilsson Model for spherical nuclei.

V.6.3 Odd-Odd Nuclei

In odd-odd nuclei, there are two unpaired nucleons - a proton and a neutron. The low-energy states are then formed from the various couplings of these two. Clearly the situation is very complex.[43] As a result, odd-odd nuclei are least studied and less understood than odd-A and even-even nuclei. In particular, nuclear models describing spherical odd-odd nuclei are not available. Therefore, special treatments must be found. Fortunately, even at low excitation energies, odd-odd nuclei have relatively dense energy levels; therefore the continuum model may be applicable.

After studying quite a few level diagrams of odd-odd nuclei from reference (38) a general systematic trend was noticed. At low excitation energies, most odd-odd nuclei are populated with levels with $J^{\pi} = 0^-, 1^-, 2^-$. Interestingly, odd-odd nuclei are the daughters of even-even nuclei which have ground state $J^{\pi} = 0^+$. According to beta decay selection rules, the decays are classified as beta decay first forbidden transitions. In other words, first forbidden transitions are the dominant decay modes for even-even nuclei to the discrete state regions of odd-odd nuclei.

Therefore, for the low energy region, with excitation energies between 0.01 Mev (due to the divergent characteristics of Equation (4.3), U can not be zero, and is set at 0.01 Mev) and E_d, the continuum model was used; however only first forbidden transitions were considered to states below the departure energy. The ground state (zero energy) was considered as an extra decay channel, if it had the correct spin and parity values according to selection rules for either allowed or first forbidden transition.

For states above the departure energy, only levels which could arise from allowed transitions were considered as was done for other type of nuclides.

V.7 Continuum Region

The probability of beta decay (allowed) can be taken as,

$$P(E) \propto E^5 \rho(U, J_D), \tag{5.1}$$

where

$P(E)$ = probability of emission of a beta with end-point energy E,

E^5 = probability of emission of a beta to a given daughter nuclide state which is proportional to the decay constant (λ) for that state,

$\rho(U, J_D)$ = angular-momentum-dependent level density as defined by Equation (4.1),

U = effective excitation energy as defined by Equation (4.8),

J_D = angular momentum of daughter level.

Let $E_\gamma = Q - E$ = excitation energy of daughter nuclide, available as gamma decay energy, therefore, $U = E_\gamma - P(N) - P(Z)$ as in Equation (4.8).

Equation (5.1) can be written as,

$$P(E) = C' E^5 \rho(U, J_D), \tag{5.2}$$

where C' = proportional constant.

Equation (5.2) can be written as,

$$P(Q - E_\gamma) = C' (Q - E_\gamma)^5 \rho(E_\gamma - P[N] - P[Z], J_D). \tag{5.3}$$

The expected value of beta end-point energy ($E = Q - E_\gamma$) is then

$$\overline{Q - E_\gamma} = \frac{\int_{E_d}^{Q} C' (Q - E_\gamma)(Q - E_\gamma)^5 \rho(E_\gamma - P[N] - P[Z], J_D) dE_\gamma}{\int_{E_d}^{Q} C' (Q - E_\gamma)^5 \rho(E_\gamma - P[N] - P[Z], J_D) dE_\gamma}, \tag{5.4}$$

where E_d = departure energy, and $d(Q - E_\gamma) = -dE_\gamma$. Since C' and Q

are constants, Equation (5.4) becomes

$$Q - \overline{E_\gamma} = \frac{\int_{E_d}^{Q} (Q - E_\gamma)^6 \rho(E_\gamma - P[N] - P[Z], J_D) dE_\gamma}{\int_{E_d}^{Q} (Q - E_\gamma)^5 \rho(E_\gamma - P[N] - P[Z], J_D) dE_\gamma} . \tag{5.5}$$

Only allowed transitions will be considered in this region, and according to selection rules, J_D can have the values J_P, J_P+1, J_P-1. However, J_P-1 can not be less than zero; therefore, for some nuclei, J_D can only have J_P and J_P+1. Here, J_P is the ground state (or metastable state) angular momentum of the parent nuclide. Then Equation (5.5) can be used to calculate the average beta end-point energy for each J_D (using a 100-mesh-point Simpson's rule integration). After E_γ (= Q - E) for each J_D had been calculated, the level density for each J_D at that E_γ can be found as $(1/2)\rho[E_\gamma - P(N) - P(Z), J_D]$. The factor 1/2 comes from assuming equal probability for the two possible parities.

V.8 Average Beta and Gamma Decay Energies per Disintegration Calculation

Since we are considering only average beta and gamma decay energies per disintegration, gamma cascade effects do not need to be considered.

A fictitious beta decay level diagram for a nucleus can readily be constructed by the methods presented in V.6 and V.7. But before proceeding with the calculation, one more point needs to be considered, namely, the competition between allowed and first forbidden transitions

in the discrete states region. In other words, we must attach appropriate hindrance factors (HF) to the first forbidden transitions in order to put them on the same basis as allowed transitions.

Let us denote $f_o t_o$ and $f_1 t_1$ as the allowed and first forbidden transition ft values respectively. One can expect an increase in ft by about a factor of 100 from one degree of forbiddenness to the next,[3,43,44] then

$$f_1 t_1 / f_o t_o \cong 10^2. \tag{5.6}$$

From Equation (5.6), we can write

$$t_o / t_1 = 10^{-2} (f_1 / f_o). \tag{5.7}$$

Define f_1/f_o = Sc, then Equation (5.7) becomes

$$\lambda_1 / \lambda_o = 0.01\text{Sc}, \tag{5.8}$$

where λ_o and λ_1 are the decay constants for allowed and first forbidden transitions respectively. A table listing of Sc can be found in reference (45), but it is not sufficient for our purpose, because Sc is a function of charge and energy, but only Sc for some charge and energy values are listed. Therefore, a least-squares fit to a quadratic function of energy ($\text{Sc} = B_o + B_1 E_x + B_2 E_x^2$), using values from the table was performed and results are listed in Appendix I. By defining HF = 0.01Sc and taking the probability of allowed beta decay as $E^5 \rho(U, J_D)$, then the probability of first forbidden beta decay can be taken as $(\text{HF}) E^5 \rho(U, J_D)$.

With the availablities of hindrance factors and the fictitious decay level diagram, the average gamma decay energy of a nucleus can readily be calculated. The probability of beta decay to each level

is calculated first by using either $E^5\rho(U,J_D)$ or $(HF)E^5\rho(U,J_D)$; then by normalizing the total probability to one, relative probabilities of decay to levels can be deduced. Multiplying each E_γ by its relative probability and summing will give the average gamma decay energy per disintegration.

For average beta decay energy, it is not that easy, because an antineutrino carries away part of the energy. Therefore, before applying the same procedures as above, we must first find out the net energy actually carried by the electron for each level.

The probability of beta emission with total relativitic energy, in electron rest energy units, between W' and $W' + dW'$ is[18,46,47]

$$\Psi(W') = (A_o + A_1W' + A_2W'^2)W'(W'_o - W')^2K(W'), \tag{5.9}$$

where A_o, A_1, A_2 = constants (reproduced in Appendix II),

W'_o = maximum value of W',

$K(W')$ = shape factors; for allowed transitions, $K(W') = 1.0$;

for first forbidden transitions,

$K(W') = (W'^2 - 1) + (W'_o - W')^2$.

We can now write the average kinetic beta energy as

$$< W' - 1 > = \frac{\int_1^{W'_o} (W' - 1)\Psi(W')dW'}{\int_1^{W'_o} \Psi(W')dW'}, \tag{5.10}$$

where the "1" is the electron rest mass energy in electron rest energy units.

Due to the definition of Q used in this study, namely, atomic mass

excess (2.2), electron rest mass energy is of no concern here. In other words, we can let $W' - 1 = W$, and then $W_0 = W_0' - 1$ is the beta end-point energy in electron rest energy units. Then, Equation (5.10) becomes

$$< W > = \frac{\int_0^{W_0} W\Psi(W + 1)dW}{\int_0^{W_0} \Psi(W + 1)dW} . \tag{5.11}$$

For allowed transitions, Equation (5.11) becomes

$$< W > = \frac{\int_0^{W_0} W[A_0 + A_1(W + 1) + A_2(W + 1)^2](W + 1)(W_0 - W)^2 dW}{\int_0^{W_0} [A_0 + A_1(W + 1) + A_2(W + 1)^2](W + 1)(W_0 - W)^2 dW}, \tag{5.12}$$

and for first forbidden transitions, Equation (5.11) becomes

$$< W > = \frac{\int_0^{W_0} W[A_0 + A_1(W + 1) + A_2(W + 1)^2](W + 1)(W_0 - W)^2}{\int_0^{W_0} [A_0 + A_1(W + 1) + A_2(W + 1)^2](W + 1)(W_0 - W)^2} \times$$

$$\times \frac{[\{(W + 1)^2 - 1\} + (W_0 - W)^2]dW}{[\{(W + 1)^2 - 1\} + (W_0 - W)^2]dW} . \tag{5.13}$$

Again the net energy carried away by electron for each energy level (end-point energy) can be found from Equation (5.12) or (5.13) by using a 100-mesh-point Simpson's rule integration. Following the same procedures as in calculating gamma decay energy, average beta decay energy per disintegration can be found.

One final point should be mentioned here: there are some metastable states which will decay to two different daughters (branching effect). In that case, average decay energies calculated above will be weighted by branching ratios to yield the final results.

V.9 Procedures

There are only five major steps to take in performing the calculation of predicted decay energies. These are

1). Calculations of departure energy from departure level density (30 levels/MeV, Equation 4.3) and parameter a (Equation 4.10 or 4.11 depends on whether the nuclide is spherical or deformed) for each nuclide (daughter) under consideration. Inputs are Q values and ground state spin values of the parent nuclei as well as pairing energies and shell corrections for protons and neutrons. Computer program WBGEA (Appendix IV).

2). For the continuum region, there are three averaged levels, namely, $J_D = J_P$, J_P-1, J_P+1. For each J_D, beta end-point energy (Equation 5.5) and level density ($[1/2]\rho\{E_\gamma-P(N)-P(Z),J_D\}$) at that beta end-point energy are calculated. Inputs are Q values and ground state spin values of the parent nuclei as well as departure energies and parameter a of the daughter nuclei; also pairing energies for protons and neutrons. Computer program WBGEB (Appendix IV).

3). Step two gives the three averaged levels for the continuum region and levels for the discrete region can be gotten by using nuclear models. Step three will proceed with the development of fictitious decay level diagram for each nuclide. A typical fictitious decay level diagram is shown in Figure 5-2.

Note here that for same nuclide whose Q values are too low to have a continuum region, they are ignored at step two and are only treated here for discrete states region.

4). From those fictitious decay level diagrams developed by step three, average beta decay energies (Equation 5.12 or 5.13), level by level, are obtained. By using either $E^5\rho(U,J_D)$ or $(HF)E^5\rho(U,J_D)$ as weights, average beta and gamma decay energies per disintegration can finally be evaluated. Computer program ABGE (Appendix IV).

5). Treatments of branching effects in decay energies for some metastable states must be carried out.

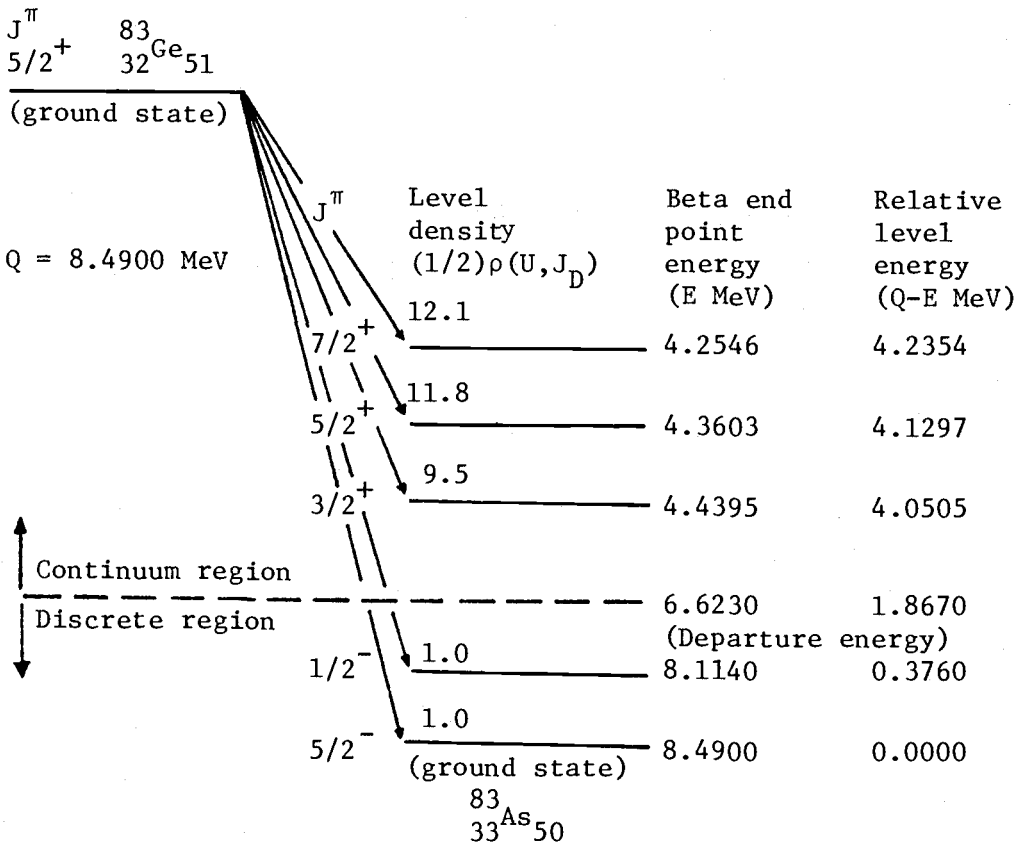

FIGURE 5-2 A typical (ground state to ground state) fictitious beta-decay level diagram for ^{83}Ge to ^{83}As (energy levels are not drawn to scale).

VI. COMPARISON WITH EXPERIMENT

VI.1 Introduction

Theoretical predictions must be validated by experiments; therefore, a comparison between them is in order. One hundred thirty-six nuclei with experimental measurements will be used to make such a comparison. They are listed in Table 6-1. The last column of Table 6-1 gives their differences in non-dimensional form (differences divided by Q).

Figures 6-1, 6-2, and 6-3 are the cumulative normal curves of $(E_{Tcal.}-E_{Texp.})/Q$, $(E_{\beta cal.}-E_{\beta exp.})/Q$, and $(E_{\gamma cal.}-E_{\gamma exp.})/Q$ respectively. An estimate of the standard deviation can be obtained from the difference between the 50% point and the 84.13% point, or the 50% and the 15.87% point.

The standard deviation can be expressed as,[48]

$$\sigma = \sqrt{\frac{\sum_{n=1}^{k} x_n^2 - k\bar{x}^2}{k-1}}, \tag{6.1}$$

where k = 136, $x_n = (E_{cal.}-E_{exp.})/Q$, and $\bar{x}$ = average of x_n. Standard deviations calculated by using Equation (6.1) are listed in Table 6-2. Referring to Table 6-2, clearly, $\sigma^2_{E_T} \neq \sigma^2_{E_\beta} + \sigma^2_{E_\gamma}$ which implies the σ's are correlated. Conservation of energy requires

$$E_\beta + E_{\bar{\nu}} + E_\gamma = Q, \tag{6.2}$$

TABLE 6-1 Theoretical and experimental decay energies. $E_T=E_\beta+E_\gamma$.

Nuclide	$E_{\beta cal.}$ (Mev)	$E_{\gamma cal.}$ (Mev)	$E_{\beta exp.}$ (Mev)	$E_{\gamma exp.}$ (Mev)	$E_{Tcal.}$ (Mev)	$E_{Texp.}$	$E_{Tcal.}-E_{Texp.}$ Q
79320	1.7255	.2421	1.8927	.2514	1.9676	2.1441	-.0425
81330	1.6209	.0545	1.6694	0.0000	1.6754	1.6694	.0016
83341	1.5853	.2089	1.3017	.9093	1.7942	2.2110	-.1087
83340	.9853	1.2773	.4419	2.5593	2.2626	3.0012	-.2043
85350	.2607	2.0323	.9949	.0647	2.2930	1.0596	.4405
85361	.2242	.2918	.2261	.1832	.5160	.4093	.1076
85360	.2563	0.0000	.2506	.0022	.2563	.2528	.0051
87350	1.8265	2.3726	2.1356	1.7263	4.1991	3.8619	.0519
87360	1.1033	1.2813	1.3345	.7926	2.3846	2.1271	.0662
89360	1.2963	1.9020	1.2412	2.0631	3.1983	3.3043	-.0215
89370	1.3826	1.2876	.9293	2.2890	2.6702	3.2183	-.1222
89380	.5947	0.0000	.5820	0.0000	.5947	.5820	.0085
91360	1.5215	2.6997	2.5770	.7236	4.2212	3.3014	.1484
91370	1.5446	2.1518	1.3342	2.7332	3.6964	4.0674	-.0651
91380	.7011	.9412	.6523	.6954	1.6423	1.3477	.1098
91390	.6160	0.0000	.6060	.0027	.6160	.6087	.0047
93380	.9903	1.5679	1.1611	1.3950	2.5582	2.5561	.0005
93390	1.0644	.3716	1.1845	.0896	1.4360	1.2741	.0560
95390	1.2129	1.5725	1.7457	.4883	2.7854	2.2340	.1245
95410	.2138	.2696	.0436	.7658	.4834	.8094	-.3522
97390	1.6289	2.9328	2.1621	.9350	4.5617	3.0971	.2196
97400	.2566	1.8929	.7071	.1818	2.1495	.8889	.4744
97410	.6441	.2677	.4679	.6770	.9118	1.1449	-.1206
99400	1.6421	.6953	1.6205	.7937	2.3374	2.4142	-.0172
99411	1.2474	1.0630	.9537	1.9943	2.3104	2.9480	-.1597
99410	.5407	2.1896	1.5225	.1997	2.7303	1.7222	.2782
101410	.7785	2.6119	1.9006	.3300	3.3904	2.2306	.2538
101420	.4314	1.6248	.5950	1.3862	2.0562	1.9812	.0267
101430	.5057	.2641	.4800	.3363	.7698	.8163	-.0286
103440	.2821	0.0000	.0675	.4900	.2821	.5575	-.3610
105440	.1503	1.4317	.4126	.7877	1.5820	1.2003	.1990
105450	.1750	.0115	.1523	.0788	.1865	.2311	-.0787
107440	1.2679	.1439	1.2375	.2514	1.4118	1.4887	-.0245
107450	.3894	.0566	.4212	.3123	.4460	.7335	-.2498
109460	.4242	0.0000	.3641	.0002	.4242	.3643	.0537
111461	.1749	.3561	.1671	.4214	.5310	.5885	-.0242
111460	.6774	.5037	.8442	.0529	1.1811	.8971	.1291
111470	.3733	.0336	.3548	.0270	.4069	.3818	.0244
125501	.3374	1.3994	.7980	.3459	1.7368	1.1439	.2495
125500	.8880	.1699	.8362	.3123	1.0579	1.1485	-.0386
127501	.7023	1.4487	1.1342	.4940	2.1510	1.6282	.1602
127500	1.0740	.5138	.6746	1.4343	1.5878	2.1089	-.1681

127510	.0162	1.5186	.3181	.6443	1.5348	.9624	.3620
127520	.2243	0.0000	.2273	.0052	.2243	.2325	-.0118
129510	.2092	1.7245	.3591	1.3011	1.9337	1.6602	.1151
129521	.2951	0.0000	.2140	.0298	.2951	.2438	.0320
129520	.0537	1.3026	.5339	.0729	1.3563	.6068	.5003
131510	.3858	2.0055	.7137	1.7025	2.3913	2.4162	-.0080
131521	.7534	.2174	.1822	1.4911	.9708	1.6733	-.2889
131520	.2990	1.3646	.6717	.4229	1.6636	1.0946	.2530
133510	.6034	2.3561	.5371	3.1625	2.9595	3.6996	-.1874
133521	.9464	.9744	.5521	1.8662	1.9208	2.4183	-.1506
133520	.5738	1.4361	.8200	.9832	2.0099	1.8032	.0696
133530	.1197	1.4257	.4172	.5990	1.5454	1.0162	.3007
135530	.2770	1.9274	.3937	1.4560	2.2044	1.8497	.1308
137540	1.3231	1.1944	1.8407	.1953	2.5175	2.0360	.1108
139540	1.3509	1.6634	1.7868	.9275	3.0143	2.7143	.0615
139550	1.5324	.6940	1.7637	.3108	2.2264	2.0745	.0354
139560	.8030	.2971	.8972	.0523	1.1001	.9495	.0653
141560	.7050	1.2111	.9155	.8879	1.9161	1.8034	.0372
141570	.8710	.2636	.9899	.0328	1.1346	1.0227	.0460
141580	.2014	.0161	.1595	.0717	.2175	.2312	-.0236
143580	.5233	.0809	.4191	.2958	.6042	.7149	-.0761
143590	.3284	.0360	.3239	0.0000	.3644	.3239	.0433
145580	.5687	.9962	.6299	.7489	1.5649	1.3788	.0744
145590	.6702	.0830	.7047	.0138	.7532	.7185	.0192
147590	.6790	.9505	.7480	.8201	1.6295	1.5681	.0227
147600	.3261	0.0000	.2417	.1187	.3261	.3604	-.0383
147610	.0810	0.0000	.0630	.0001	.0810	.0631	.0797
149590	.6528	1.2973	1.1576	.2513	1.9501	1.4091	.1803
149600	.5470	.2567	.4744	.3368	.8037	.8112	-.0044
149610	.3764	.0476	.3766	.0142	.4240	.3908	.0310
151600	.9581	.0351	.6442	.8393	.9932	1.4835	-.2009
151610	.4362	.0155	.3119	.3096	.4517	.6215	-.1429
153610	.6701	.0745	.6726	.0775	.7446	.7501	-.0031
153620	.2630	0.0000	.2307	.1045	.2630	.3352	-.0897
80330	2.2385	.7267	2.5226	.6066	2.9652	3.1292	-.0288
82330	2.9216	1.0110	3.2109	.2881	3.9326	3.4990	.0586
84350	1.6328	.9653	1.2557	1.7527	2.5981	3.0084	-.0878
86350	2.3224	2.1458	1.7752	3.3179	4.4682	5.0931	-.0656
88370	1.7424	1.3584	2.0826	.6739	3.1008	2.7565	.0649
90371	1.5160	2.6824	1.1063	3.6160	4.1984	4.7223	-.0810
90370	2.0375	1.7916	1.6586	2.6604	3.8291	4.3190	-.0770
90390	.9526	.0012	.9310	.0003	.9538	.9313	.0099
92370	2.6365	1.9522	3.4593	.2614	4.5887	3.7207	.1117
92390	1.3075	.5975	1.4642	.2482	1.9050	1.7124	.0530
94390	1.5174	1.3879	1.7174	.9861	2.9053	2.7035	.0413
98410	1.7684	.5494	1.8653	.1402	2.3178	2.0055	.0681
100410	2.3971	.8918	2.0596	1.9205	3.2889	3.9801	-.1109

102430	1.7090	.5778	1.5088	.4633	2.2868	1.9721	.0699
104430	1.7703	1.3603	1.1930	1.4481	3.1306	2.6411	.0906
106451	.9778	1.2834	.3487	2.6452	2.2612	2.9939	-.1992
106450	1.3167	.4293	1.4457	.1994	1.7460	1.6451	.0285
108450	1.7064	.5742	1.8281	.7085	2.2806	2.5366	-.0569
110450	1.7556	1.3724	1.3457	2.2677	3.1280	3.6134	-.0899
112470	1.2078	1.0834	1.4289	.6638	2.2912	2.0927	.0502
118491	.6579	2.5475	1.7758	.2181	3.2054	1.9939	.2844
118490	1.7059	.2568	.6295	2.5759	1.9627	3.2054	-.2959
120491	1.1062	3.0213	2.4715	.1757	4.1275	2.6472	.2597
120490	2.1555	.5198	1.0387	3.0597	2.6753	4.0984	-.2635
128510	.5810	2.7422	.4185	3.0961	3.3232	3.5146	-.0449
130511	1.2213	2.0664	1.0932	2.4895	3.2877	3.5827	-.0590
130510	.6396	3.2689	1.2607	2.1409	3.9085	3.4016	.1020
132511	1.7340	1.5872	1.6955	2.0386	3.3212	3.7341	-.0737
132510	1.4393	2.2194	1.7221	2.0060	3.6587	3.7281	-.0124
132530	.7560	1.6394	.5247	2.2377	2.3954	2.7624	-.1025
134510	2.8638	2.4089	3.9516	0.0000	5.2727	3.9516	.1501
134530	.8816	1.9363	.6909	2.5927	2.8179	3.2836	-.1122
136530	2.3851	1.6016	1.8110	2.2135	3.9867	4.0245	-.0054
138551	.8415	2.0354	1.1469	2.0997	2.8769	3.2466	-.0587
138550	1.1299	2.7486	1.2624	2.3291	3.8785	3.5915	.0522
140550	1.7504	2.0288	1.9312	2.1311	3.7592	4.0623	-.0501
140570	.4500	2.5111	.5170	2.2048	2.9611	2.7218	.0636
142570	1.3021	1.3969	.9470	2.5647	2.6990	3.5117	-.1799
144590	1.1709	.1584	1.2628	.0310	1.3293	1.2938	.0118
146590	1.1777	1.2090	.9279	1.6349	2.3867	2.5628	-.0432
148590	1.6944	.9276	2.0435	.3000	2.6220	2.3435	.0568
84340	.4844	.5603	.5308	.4077	1.0447	.9385	.0584
88360	.8721	.7380	.2486	2.2118	1.6601	2.4604	-.2747
90360	1.3809	1.1866	1.1870	1.7491	2.5675	2.9361	-.0840
90380	.1886	.0315	.1980	0.0000	.2201	.1980	.0405
92360	1.6967	2.1056	2.4032	.7518	3.8023	3.1550	.1084
92380	.5095	.5964	.1923	1.3388	1.1059	1.5311	-.2203
94380	1.0310	.9429	.8696	1.2425	1.9739	2.1121	-.0404
102420	.3591	.0253	.3111	0.0000	.3844	.3111	.0705
106440	.0101	0.0000	.0100	0.0000	.0101	.0100	.0025
108440	.4127	.0541	.4701	.0462	.4668	.5163	-.0412
128500	.2750	.4914	.2172	.5965	.7664	.8137	-.0367
132500	.9799	.8207	.6603	1.3228	1.8006	1.9831	-.0567
132520	.1602	.0458	.0601	.2686	.2060	.3287	-.2489
134520	.3539	.3361	.1521	.8250	.6900	.9771	-.2208
138540	.7612	.8002	.6577	1.1951	1.5614	1.8528	-.1064
140560	.2346	.3580	.2803	.2169	.5926	.4972	.0922
142560	.5975	.6153	.4283	1.0127	1.2128	1.4410	-.1037
144580	.1056	.0230	.0830	.0289	.1286	.1119	.0525
146580	.2234	.3892	.2427	.3143	.6126	.5570	.0515

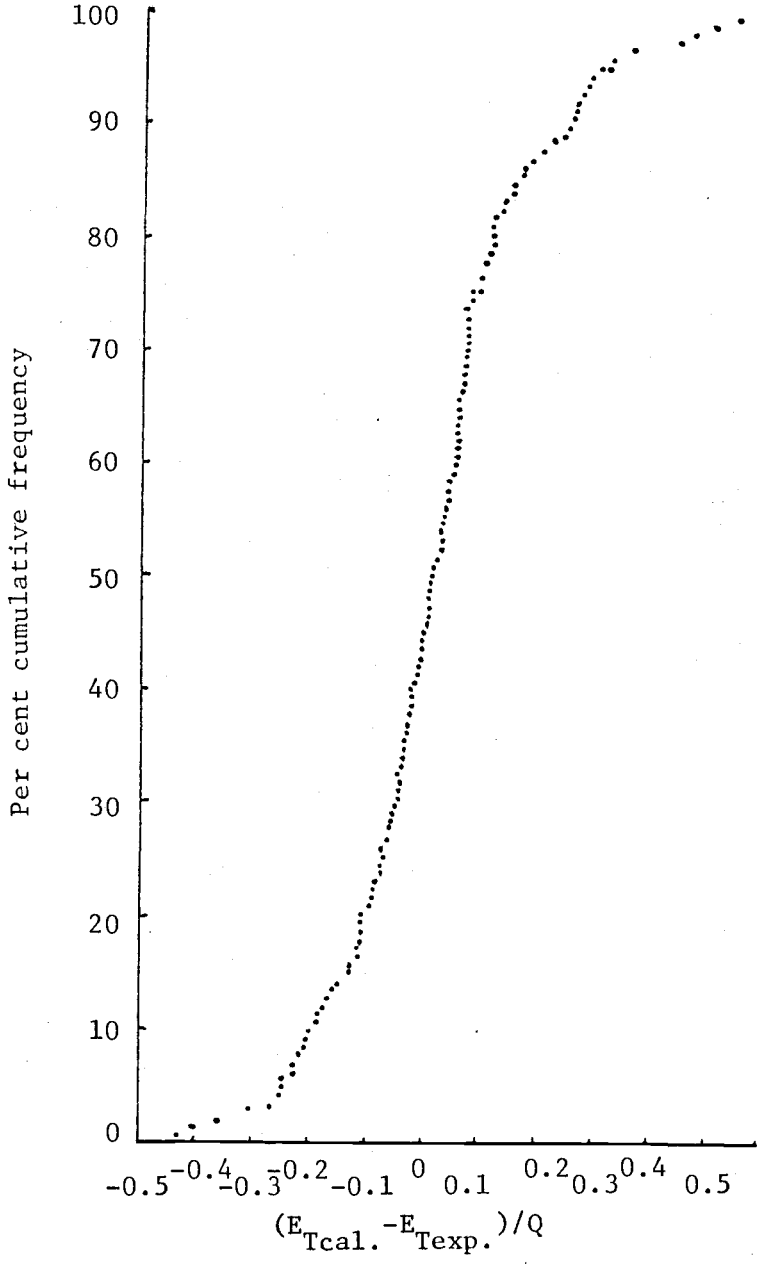

FIGURE 6-1 Cumulative normal curve (E_T).

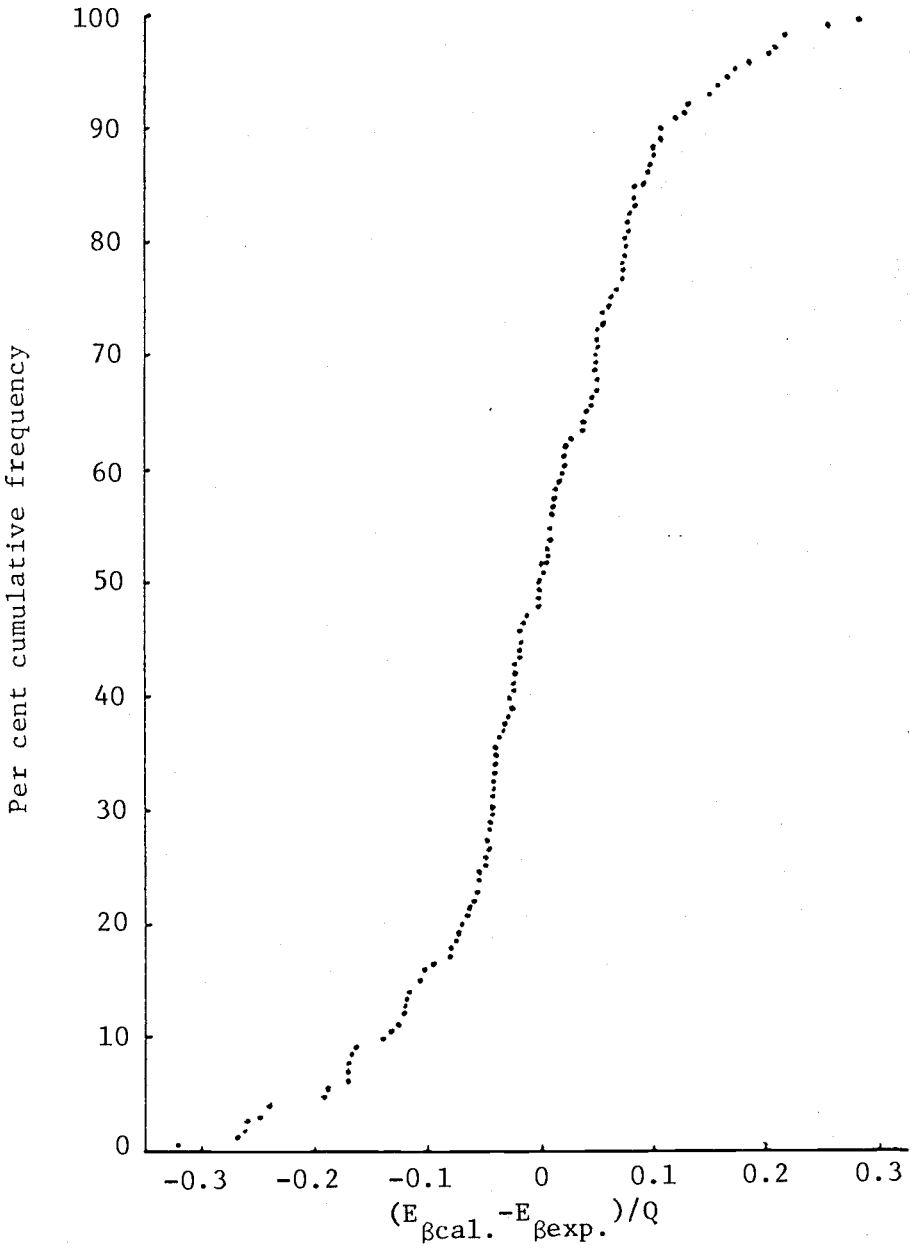

FIGURE 6-2 Cumulative normal curve (E_β).

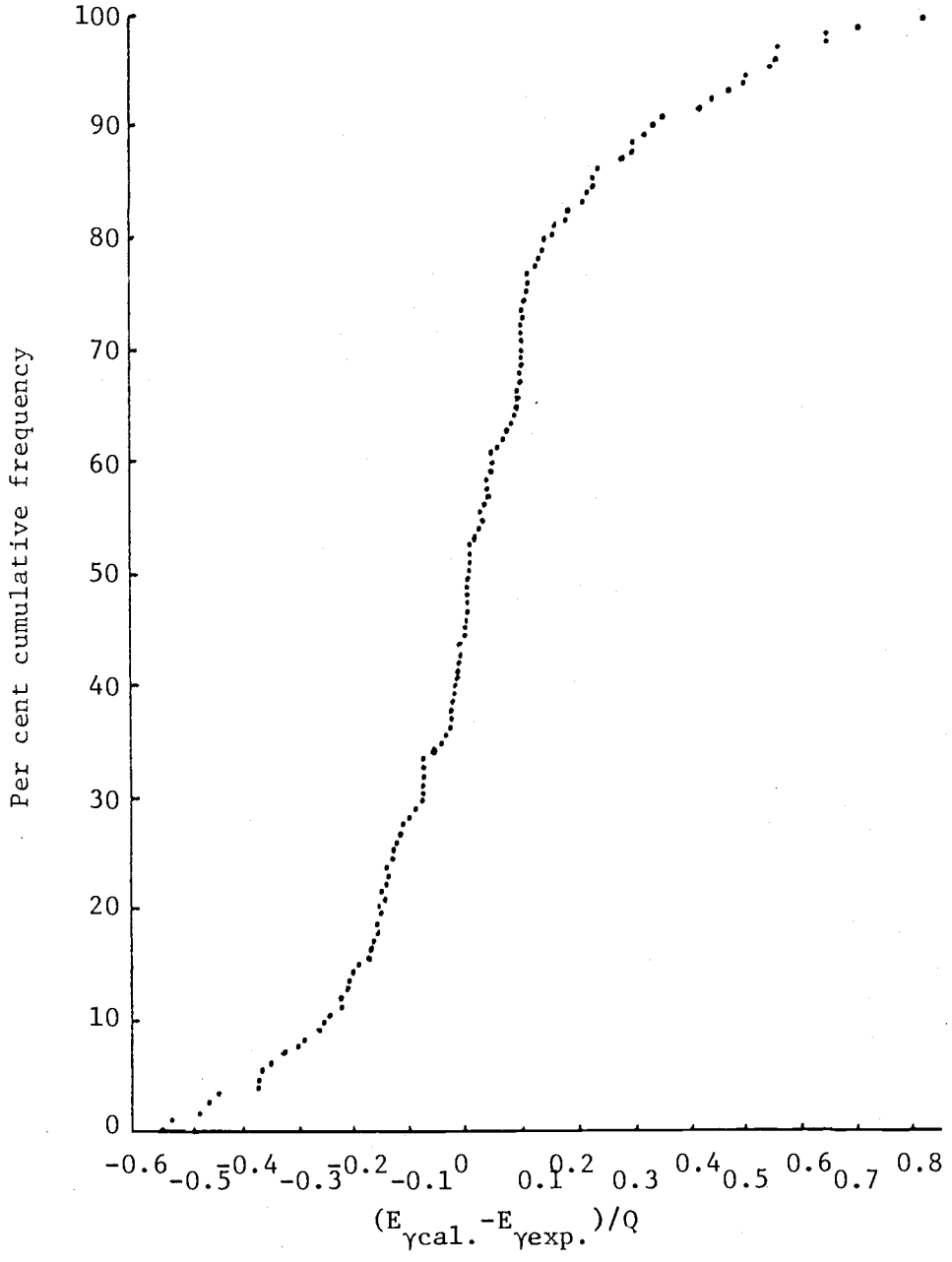

FIGURE 6-3 Cumulative normal curve (E_γ).

TABLE 6-2 Calculation of standard deviations (σ; Equation 6.1). $x_n = (E_{\theta cal.} - E_{\theta exp.})/Q$ and $\bar{x}$=average of x_n. All the numbers are dimensionless. θ denotes either β or γ or T.

	Σx_n^2	$\bar{x}$	σ
E_β	1.5214	-0.006052	0.1060
E_γ	8.2610	+0.018304	0.2467
E_T	3.3185	+0.006210	0.1567

or

$$E + E_{\gamma} = Q, \tag{6.3}$$

where $E = E_{\beta} + E_{\bar{\nu}}$ = beta end-point energy. On the average, an increase in beta end-point energy will result an increase in beta decay energy (see Equation 5.11). Since Q is constant, an increase in beta decay energy (by an increase in beta end-point energy) will necessitate a decrease in gamma decay energy (Equation 6.3) which implies the σ's should be anti-correlated. Mathematically, $\sigma^2_{E_T} \neq \sigma^2_{E_\beta} + \sigma^2_{E_\gamma}$ implies the covariance term is not zero, therefore, $\sigma^2_{E_T} = \sigma^2_{E_\beta} + \sigma^2_{E_\gamma} + 2\rho\sigma_{E_\beta}\sigma_{E_\gamma}$, where ρ can vary continuously from -1 to +1. ρ = +1 implies positive correlation (100%) which means if σ_{E_β} increases, then σ_{E_γ} will increase also. ρ = -1 implies negative (anti) correlation (100%) which means if σ_{E_β} increases, then σ_{E_γ} will decrease. In our case, ρ = -0.9091 which implies the σ's are anti-correlated (but not 100%). Since E_T is more precisely determined than E_γ, this leads simply to the observation that results on summation for E_β and E_γ will necessary be less precise than the E_T.

For some metastable states, only gamma transitions to their respective ground states occur. Since their gamma energies are measured, their standard deviations are assumed to be zero.

Even though E_β, E_γ, and their respective standard deviations are evaluated separately here, only their sum (E_T) is of interest in after-heat analysis. Therefore, it is more appropriate to perform the comparison in term of E_T and its uncertainty.

VI.2 Normal Distribution of x_n

One would like the x_n's to behave in a normal distribution about a mean of zero for two reasons:

1). A mean of zero implies the x_n's are randomly distributed; this in turn, implies there is no bias in the theoretical formulations.

2). The standard deviation calculated above can have its usual meaning, namely, 68% of the results will have uncertainties $\leq \sigma$. Otherwise, the same 68% may require two or three σ.

If the cumulative frequency of a normally distributed variable is plotted on ordinary rectangular paper the familiar S-shaped curve of Figure 6-1 is obtained. This curve is called an ogive.[49]

A Chi-Square (χ^2) test can be applied[50] to check the goodness-of-fit to normal distribution. One hundred thirty-six data points (from last column of Table 6-1) are divided into eight groups as shown in columns one to three of Table 6-3. The next step is to compute what probability a normally distributed random variable x with mean 0.00621 and standard deviation 0.1567 has of falling in each of the eight groups. To do this one standardizes the boundaries (bottom row of Figure 6-4):[50]

$$(-0.2 - 0.00621)/0.1567 = -1.32 \text{ etc.}$$

The probability (column four of Table 6-3 and top row of Figure 6-4) for each group can be calculated by considering the area under the standard normal curve between appropriate group boundaries.

TABLE 6-3 Calculation of the χ^2.

Group	Range of x_n	Number of x_n in the ith group (y_i)	Probability	Expected number of x_n in the ith group (f_i)	χ_i^2
1	less than -0.2	13	0.0934	12.7051	0.0068
2	-0.2 to -0.1	15	0.1548	21.0528	1.7396
3	-0.1 to -0.05	15	0.1112	15.1232	0.0010
4	-0.05 to 0	21	0.1246	16.9456	0.9701
5	0 to 0.05	20	0.1262	17.1632	0.4689
6	0.05 to 0.1	24	0.1155	15.7080	4.3772
7	0.1 to 0.2	15	0.1668	22.6848	2.6033
8	0.2 up	13	0.1075	14.6200	0.1795
Total		136	1.000	136	10.3464

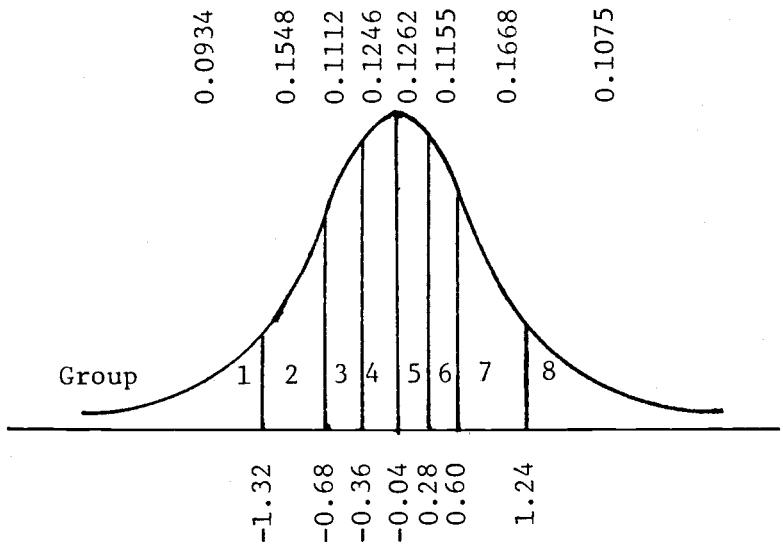

FIGURE 6-4 Calculation of probabilities (area under the standard normal curve). Top row indicates the probabilities for each group; middle row indicates the groups; and bottom row indicates the standardized boundaries for the groups.

Now, one can find the expected number (f_i, column five of Table 6-3) of x_n's in each group by simply multiplying 136 by its probability. Then[50]

$$\chi^2 = \sum_{i=1}^{8} (y_i - f_i)^2/f_i = 10.3464.$$

The number of degrees of freedom is five in this case. Normally, it is i-1, where i = 8, but since we estimate $\bar{x}$ and σ from the sample, two degrees of freedom are lost. The 5% point on a Chi-Square distribution with five degrees of freedom is 11.070. Our value, 10.3464, is less than this; the x_n's do fit well with a normal distribution.

VII. COMPARISONS OF SUMMATION CALCULATION RESULTS

VII.1 Introduction

Since the feasibility of the method has been demonstrated by comparison of predicted decay energies with experimental results, decay energies as well as their uncertainties can be readily evaluated for nuclear decays which have not been measured. They are listed in Appendix III. But how good are they when used in after-heat predictions?

ROPEY[7] is a summation method code which calculates the $H_o(t)$ and $H_1(t,T)$ (Equations 1.1 and 1.3) functions and the uncertainties in these functions. Uncertainties in these functions are estimated by determining uncertainties in the basic parameters, such as nuclear fission product yields, decay energies, and propagating them through the summation terms.

In order to simplify the decay schemes and the calculations, neutron capture by fission products is ignored in ROPEY. It has been shown[51,52,53] that neutron capture alters the results of summation calculations by only a few percent for cooling times less than 10^5 seconds and less than 2% for times less than 10^3 seconds.

Necessary data needed for comparisons can be obtained from ROPEY runs - $H_o(t)$ and $H_1(t,\infty)$ functions (pulse and infinite irradiation ^{235}U decay power respectively). "THIS STUDY" will be used to indicate the decay energy data computed using the methods developed in this thesis (listed in Appendix III). In terms of

$H_o(t)$ and $H_1(t,\infty)$ functions, comparisons between THIS STUDY, ORNL (experiments performed by Oak Ridge National Laboratory),[54.61] ENDF/B-IV, and ANS Decay-Heat Standard[55] were performed; they are shown in Figures 7-1 through 7-5 and are listed in Tables 7-1 through 7-5. Uncertainties are listed in Table 7-6.

VII.2 Comparisons of Decay Power Predictions

Comparisons of E_β and E_γ between ORNL (experiments performed by Oak Ridge National Laboratory)[54,61] and ENDF/B-IV are shown in Figure7-1 and are listed in Table 7-1; between ORNL and THIS STUDY are shown in Figure 7-2 and are listed in Table 7-2. For short decay times, ENDF/B-IV results are low in both beta and gamma decay energies in comparison with ORNL; but results from the energy file derived here are lower in beta but higher in gamma than ORNL, therefore giving offsetting effects on total decay power.

Comparisons between ENDF/B-IV and THIS STUDY are shown in Figures 7-3 and 7-4 and are listed in Tables 7-3 and 7-4. For short decay times,THIS STUDY has lower beta but higher gamma decay energies than ENDF/B-IV; but the net result is higher total energies for THIS STUDY. For decay times greater than about 60 seconds, all results indicate there are no significant differences in over-all characteristics between the decay energy files of ENDF/B-IV and THIS STUDY.

However, for short decay times, there are differences between ENDF/B-IV and THIS STUDY. But how can one tell which one

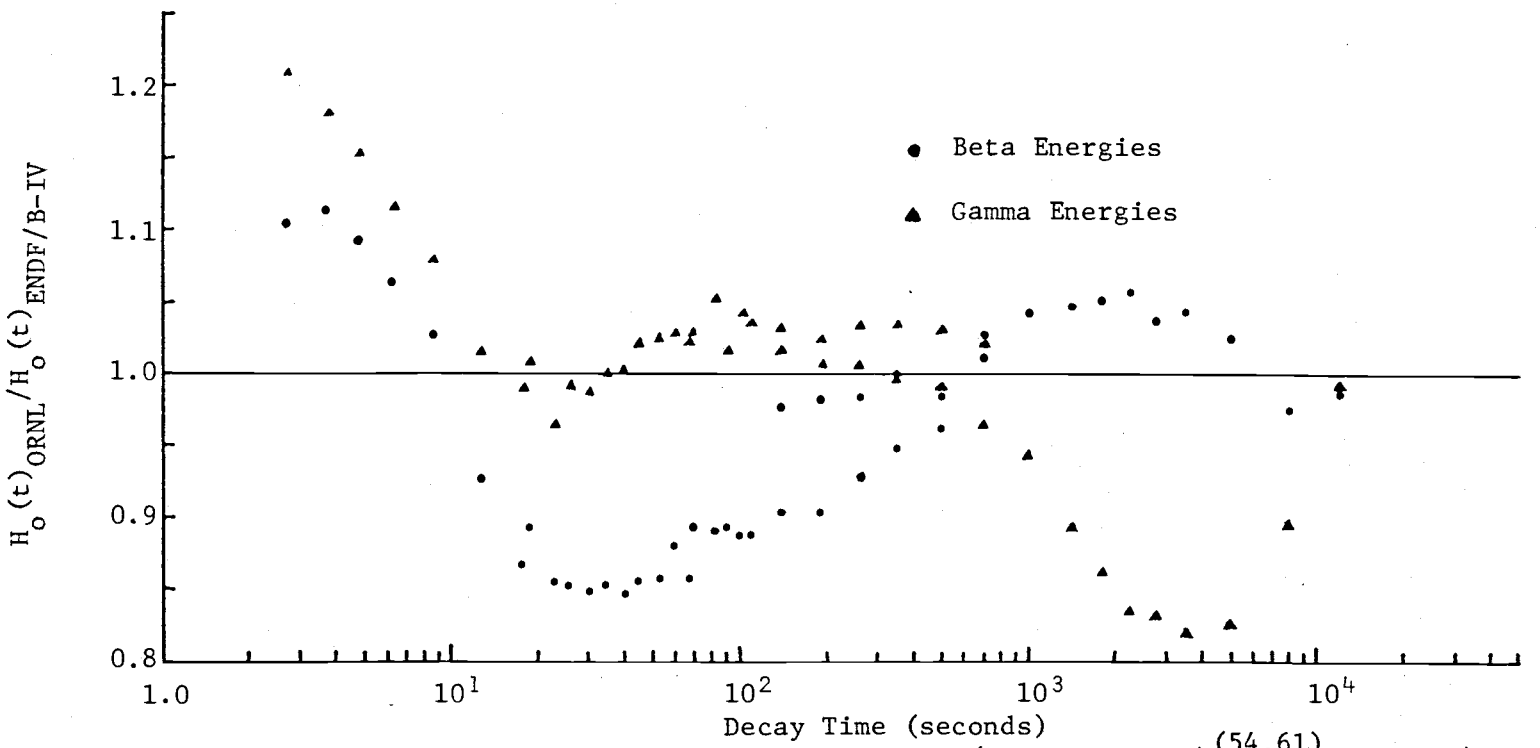

FIGURE 7-1 Ratio of ORNL corrected decay energies (beta or gamma)[54,61] to ENDF/B-IV decay energies expressed in terms of $H_o(t)$ (pulse irradiation ^{235}U decay power).

TABLE 7-1 β and γ decay energies from ORNL and ENDF/B-IV expressed in terms of $H_o(t)$ (pulse irradiation ^{235}U decay power).

Decay time (sec)	$H_o(t)_{ORNL}$ Mev/fiss/sec (E_β)	$H_o(t)_{ENDF}$ Mev/fiss/sec (E_β)	$H_o(t)_{ORNL}$ Mev/fiss/sec (E_γ)	$H_o(t)_{ENDF}$ Mev/fiss/sec (E_γ)
2.70	.2351E+00	.2128E+00	.1836E+00	.1518E+00
3.70	.1912E+00	.1717E+00	.1434E+00	.1215E+00
4.70	.1581E+00	.1446E+00	.1175E+00	.1018E+00
6.20	.1247E+00	.1174E+00	.9215E-01	.8263E-01
8.70	.9218E-01	.8971E-01	.6895E-01	.6392E-01
12.70	.5980E-01	.6449E-01	.4836E-01	.4770E-01
17.70	.4047E-01	.4659E-01	.3589E-01	.3628E-01
22.70	.3052E-01	.3568E-01	.2809E-01	.2910E-01
30.20	.2188E-01	.2578E-01	.2195E-01	.2222E-01
40.20	.1561E-01	.1841E-01	.1675E-01	.1673E-01
52.70	.1145E-01	.1334E-01	.1303E-01	.1268E-01
67.70	.8463E-02	.9874E-02	.9925E-02	.9718E-02
83.00	.6858E-02	.7698E-02	.8157E-02	.7761E-02
100.00	.5422E-02	.6099E-02	.6516E-02	.6264E-02
18.70	.3918E-01	.4389E-01	.3483E-01	.3453E-01
25.70	.2645E-01	.3104E-01	.2571E-01	.2593E-01
34.70	.1867E-01	.2191E-01	.1938E-01	.1939E-01
44.70	.1389E-01	.1623E-01	.1532E-01	.1502E-01
54.70	.1124E-01	.1276E-01	.1251E-01	.1219E-01
69.70	.8518E-02	.9532E-02	.9675E-02	.9416E-02
89.70	.6241E-02	.6991E-02	.7211E-02	.7106E-02
110.00	.4807E-02	.5404E-02	.5788E-02	.5595E-02
140.00	.3573E-02	.3958E-02	.4288E-02	.4162E-02
190.00	.2404E-02	.2661E-02	.2881E-02	.2816E-02
260.00	.1663E-02	.1791E-02	.1939E-02	.1878E-02
350.00	.1196E-02	.1261E-02	.1344E-02	.1302E-02
500.00	.8256E-03	.8588E-03	.9061E-03	.8796E-03
700.00	.6191E-03	.6117E-03	.6480E-03	.6361E-03
140.00	.3870E-02	.3958E-02	.4221E-02	.4162E-02
190.00	.2610E-02	.2661E-02	.2838E-02	.2816E-02
260.00	.1763E-02	.1791E-02	.1885E-02	.1878E-02
350.00	.1261E-02	.1261E-02	.1301E-02	.1302E-02
500.00	.8480E-03	.8588E-03	.8696E-03	.8796E-03
700.00	.6290E-03	.6117E-03	.6134E-03	.6361E-03
1000.00	.4461E-03	.4275E-03	.4381E-03	.4646E-03
1400.00	.3145E-03	.2999E-03	.3105E-03	.3484E-03
1800.00	.2375E-03	.2257E-03	.2401E-03	.2787E-03
2250.00	.1822E-03	.1720E-03	.1880E-03	.2254E-03
2750.00	.1379E-03	.1327E-03	.1522E-03	.1836E-03
3500.00	.9971E-04	.9566E-04	.1155E-03	.1408E-03
5000.00	.5989E-04	.5848E-04	.7616E-04	.9209E-04
8000.00	.3092E-04	.3168E-04	.4486E-04	.5001E-04
12000.00	.1939E-04	.1962E-04	.2769E-04	.2789E-04

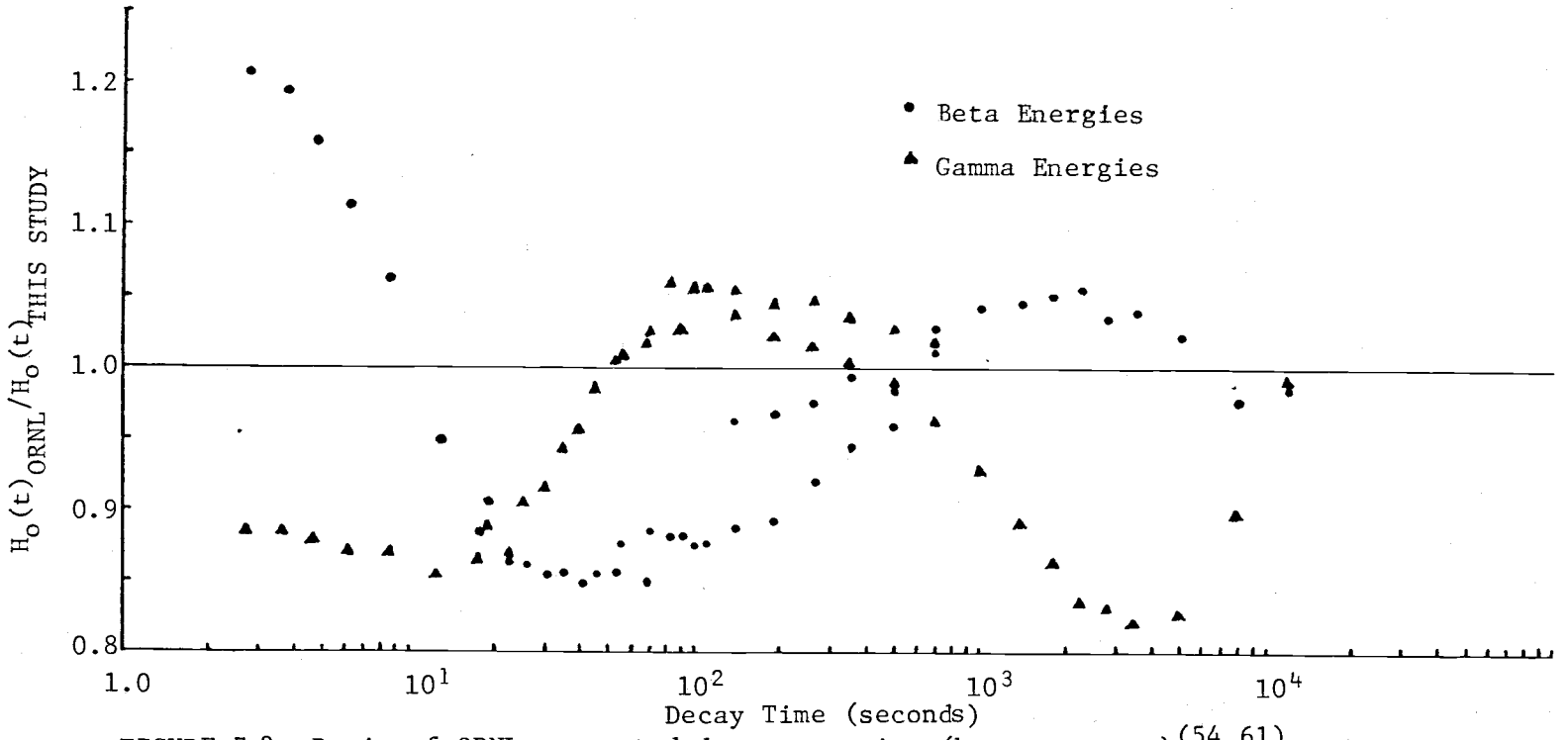

FIGURE 7-2 Ratio of ORNL corrected decay energies (beta or gamma)[54,61] to THIS STUDY decay energies expressed in terms of $H_o(t)$ (pulse irradiation ^{235}U decay power).

TABLE 7-2 β and γ decay energies from ORNL and THIS STUDY expressed in terms of $H_o(t)$ (pulse irradiation ^{235}U decay power).

Decay time (sec)	$H_o(t)_{ORNL}$ Mev/fiss/sec (E_β)	$H_o(t)_{THIS\ STUDY}$ Mev/fiss/sec (E_β)	$H_o(t)_{ORNL}$ Mev/fiss/sec (E_γ)	$H_o(t)_{THIS\ STUDY}$ Mev/fiss/sec (E_γ)
2.70	.2351E+00	.1949E+00	.1836E+00	.2078E+00
3.70	.1912E+00	.1601E+00	.1434E+00	.1622E+00
4.70	.1581E+00	.1364E+00	.1175E+00	.1334E+00
6.20	.1247E+00	.1121E+00	.9215E-01	.1058E+00
8.70	.9218E-01	.8670E-01	.6895E-01	.7922E-01
12.70	.5980E-01	.6302E-01	.4836E-01	.5666E-01
17.70	.4047E-01	.4586E-01	.3589E-01	.4144E-01
22.70	.3052E-01	.3529E-01	.2809E-01	.3230E-01
30.20	.2188E-01	.2562E-01	.2195E-01	.2392E-01
40.20	.1561E-01	.1839E-01	.1675E-01	.1750E-01
52.70	.1145E-01	.1340E-01	.1303E-01	.1295E-01
67.70	.8463E-02	.9963E-02	.9925E-02	.9746E-02
83.00	.6858E-02	.7792E-02	.8157E-02	.7695E-02
100.00	.5422E-02	.6186E-02	.6516E-02	.6165E-02
18.70	.3918E-01	.4326E-01	.3483E-01	.3919E-01
25.70	.2645E-01	.3076E-01	.2571E-01	.2839E-01
34.70	.1867E-01	.2183E-01	.1938E-01	.2057E-01
44.70	.1389E-01	.1625E-01	.1532E-01	.1556E-01
54.70	.1124E-01	.1282E-01	.1251E-01	.1241E-01
69.70	.8518E-02	.9623E-02	.9675E-02	.9426E-02
89.70	.6241E-02	.7083E-02	.7211E-02	.7021E-02
110.00	.4807E-02	.5485E-02	.5788E-02	.5491E-02
140.00	.3573E-02	.4019E-02	.4288E-02	.4070E-02
190.00	.2404E-02	.2696E-02	.2881E-02	.2760E-02
260.00	.1663E-02	.1806E-02	.1939E-02	.1856E-02
350.00	.1196E-02	.1266E-02	.1344E-02	.1298E-02
500.00	.8256E-03	.8592E-03	.9061E-03	.8821E-03
700.00	.6191E-03	.6116E-03	.6480E-03	.6386E-03
140.00	.3870E-02	.4019E-02	.4221E-02	.4070E-02
190.00	.2610E-02	.2696E-02	.2838E-02	.2760E-02
260.00	.1763E-02	.1806E-02	.1885E-02	.1856E-02
350.00	.1261E-02	.1266E-02	.1301E-02	.1298E-02
500.00	.8480E-03	.8592E-03	.8696E-03	.8821E-03
700.00	.6290E-03	.6116E-03	.6134E-03	.6386E-03
1000.00	.4461E-03	.4277E-03	.4381E-03	.4658E-03
1400.00	.3145E-03	.3004E-03	.3105E-03	.3485E-03
1800.00	.2375E-03	.2262E-03	.2401E-03	.2784E-03
2250.00	.1822E-03	.1725E-03	.1880E-03	.2250E-03
2750.00	.1379E-03	.1330E-03	.1522E-03	.1832E-03
3500.00	.9971E-04	.9589E-04	.1155E-03	.1405E-03
5000.00	.5989E-04	.5856E-04	.7616E-04	.9197E-04
8000.00	.3092E-04	.3169E-04	.4486E-04	.4999E-04
12000.00	.1939E-04	.1963E-04	.2769E-04	.2788E-04

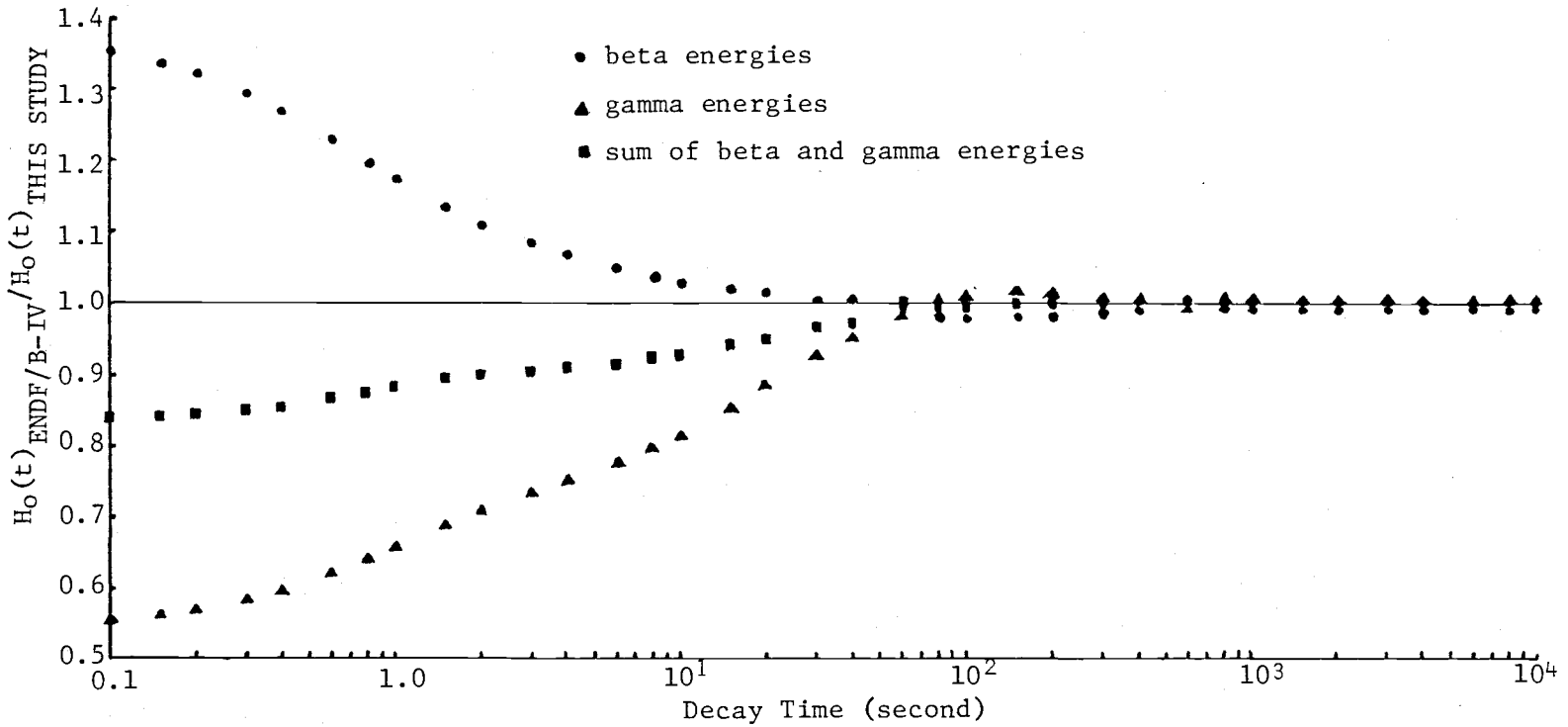

FIGURE 7-3 Ratio of ENDF/B-IV decay energies (beta or gamma or sum) to THIS STUDY decay energies expressed in terms of $H_o(t)$ (pulse irradiation ^{235}U decay power).

TABLE 7-3 β and γ and total decay energies from ENDF/B-IV and THIS STUDY expressed in terms of $H_o(t)$ (pulse irradiation ^{235}U decay power).

Decay time (sec)	$H_o(t)$ ENDF/B-IV (Mev/fiss) (E_β)	$H_o(t)$ STUDY (E_β)	$H_o(t)$ ENDF/B-IV (E_γ)	$H_o(t)$ STUDY (E_γ)	$H_o(t)$ ENDF/B-IV ($E_\beta+E_\gamma$)	$H_o(t)$ STUDY ($E_\beta+E_\gamma$)
0.	9.273E-01	6.674E-01	7.056E-01	1.291E+00	1.633E+00	1.959E+00
1.00E-01	8.080E-01	5.963E-01	6.107E-01	1.092E+00	1.419E+00	1.688E+00
1.50E-01	7.583E-01	5.664E-01	5.715E-01	1.010E+00	1.330E+00	1.576E+00
2.00E-01	7.141E-01	5.395E-01	5.366E-01	9.374E-01	1.251E+00	1.477E+00
3.00E-01	6.394E-01	4.936E-01	4.780E-01	8.162E-01	1.117E+00	1.310E+00
4.00E-01	5.791E-01	4.559E-01	4.309E-01	7.201E-01	1.010E+00	1.176E+00
6.00E-01	4.893E-01	3.980E-01	3.613E-01	5.806E-01	8.506E-01	9.786E-01
8.00E-01	4.264E-01	3.559E-01	3.131E-01	4.868E-01	7.395E-01	8.427E-01
1.00E+00	3.802E-01	3.238E-01	2.779E-01	4.207E-01	6.581E-01	7.445E-01
1.50E+00	3.045E-01	2.682E-01	2.205E-01	3.187E-01	5.250E-01	5.869E-01
2.00E+00	2.571E-01	2.312E-01	1.850E-01	2.598E-01	4.421E-01	4.909E-01
3.00E+00	1.984E-01	1.829E-01	1.412E-01	1.915E-01	3.396E-01	3.744E-01
4.00E+00	1.625E-01	1.521E-01	1.148E-01	1.522E-01	2.773E-01	3.043E-01
6.00E+00	1.204E-01	1.148E-01	8.470E-02	1.087E-01	2.051E-01	2.235E-01
8.00E+00	9.607E-02	9.258E-02	6.813E-02	8.516E-02	1.642E-01	1.777E-01
1.00E+01	7.979E-02	7.746E-02	5.747E-02	7.016E-02	1.373E-01	1.476E-01
1.50E+01	5.504E-02	5.400E-02	4.169E-02	4.857E-02	9.673E-02	1.026E-01
2.00E+01	4.096E-02	4.042E-02	3.261E-02	3.673E-02	7.358E-02	7.715E-02
3.00E+01	2.598E-02	2.582E-02	2.236E-02	2.409E-02	4.834E-02	4.990E-02
4.00E+01	1.852E-02	1.850E-02	1.682E-02	1.760E-02	3.533E-02	3.610E-02
6.00E+01	1.142E-02	1.150E-02	1.106E-02	1.118E-02	2.248E-02	2.268E-02
8.00E+01	8.056E-03	8.149E-03	8.088E-03	8.034E-03	1.614E-02	1.618E-02
1.00E+02	6.099E-03	6.186E-03	6.264E-03	6.165E-03	1.236E-02	1.235E-02
1.50E+02	3.618E-03	3.673E-03	3.815E-03	3.730E-03	7.433E-03	7.404E-03
2.00E+02	2.491E-03	2.523E-03	2.635E-03	2.585E-03	5.126E-03	5.108E-03
3.00E+02	1.508E-03	1.517E-03	1.569E-03	1.557E-03	3.077E-03	3.074E-03
4.00E+02	1.088E-03	1.090E-03	1.117E-03	1.117E-03	2.205E-03	2.207E-03
6.00E+02	7.136E-04	7.135E-04	7.345E-04	7.374E-04	1.448E-03	1.451E-03
8.00E+02	5.354E-04	5.354E-04	5.641E-04	5.661E-04	1.100E-03	1.102E-03
1.00E+03	4.275E-04	4.277E-04	4.646E-04	4.658E-04	8.921E-04	8.934E-04
1.50E+03	2.780E-04	2.785E-04	3.281E-04	3.281E-04	6.061E-04	6.066E-04
2.00E+03	1.990E-04	1.995E-04	2.526E-04	2.522E-04	4.517E-04	4.517E-04
3.00E+03	1.181E-04	1.184E-04	1.672E-04	1.668E-04	2.853E-04	2.852E-04
4.00E+03	7.953E-05	7.970E-05	1.206E-04	1.204E-04	2.002E-04	2.001E-04
6.00E+03	4.577E-05	4.581E-05	7.317E-05	7.311E-05	1.189E-04	1.189E-04
8.00E+03	3.168E-05	3.169E-05	5.001E-05	4.999E-05	8.169E-05	8.168E-05
1.00E+04	2.422E-05	2.423E-05	3.656E-05	3.655E-05	6.078E-05	6.077E-05

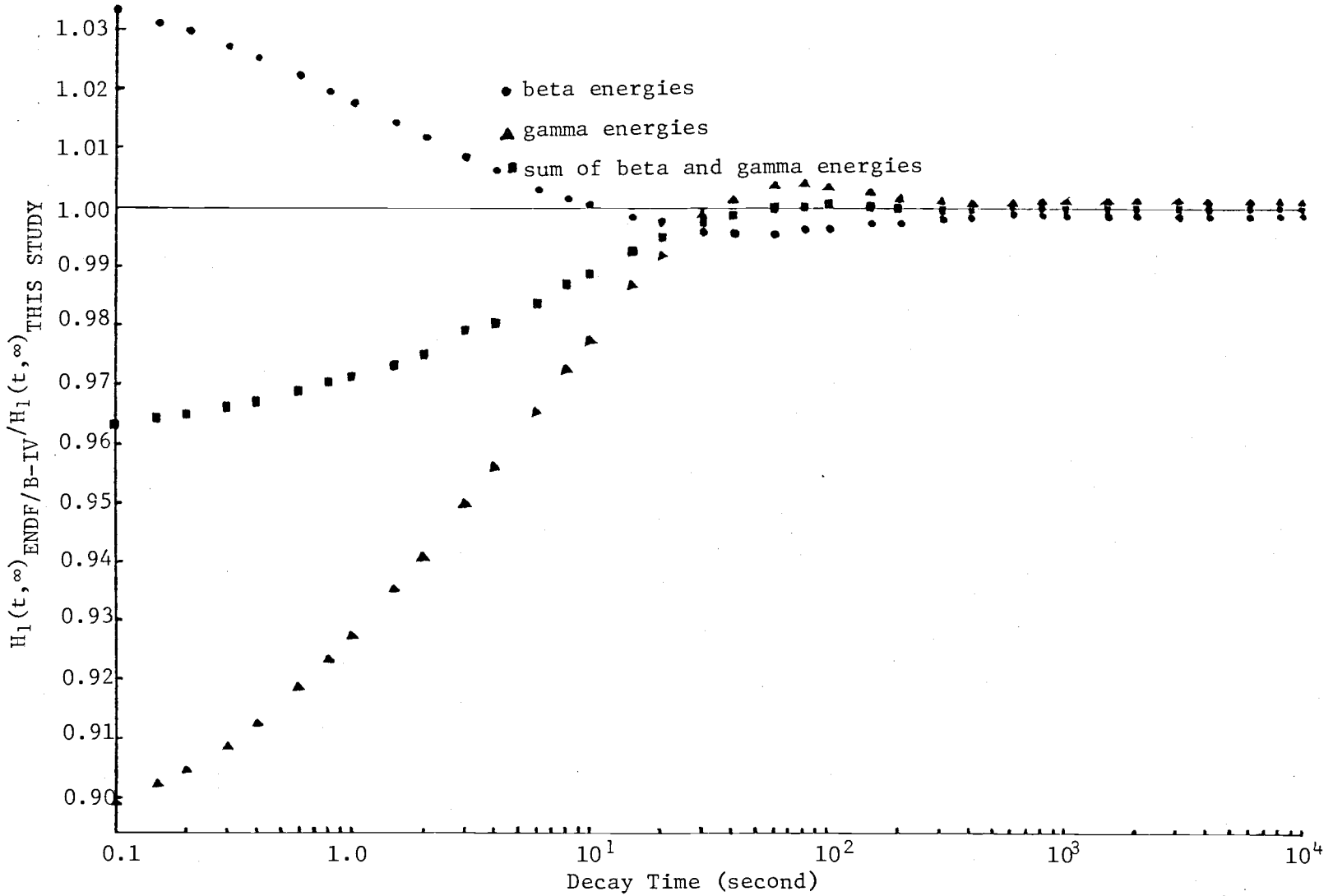

FIGURE 7-4 Ratio of ENDF/B-IV decay energies (beta or gamma or sum) to THIS STUDY decay energies expressed in terms of $H_1(t,\infty)$ (infinite irradiation ^{235}U decay power).

TABLE 7-4 β and γ and total decay energies from ENDF/B-IV and THIS STUDY expressed in terms of $H_1(t,\infty)$ (infinite irradiation ^{235}U decay power).

Decay time (sec)	$H_1(t,\infty)$ ENDF/B-IV (E_β)	$H_1(t,\infty)$ STUDY (E_β)	$H_1(t,\infty)$ ENDF/B-IV (E_γ)	$H_1(t,\infty)$ STUDY (E_γ)	$H_1(t,\infty)$ ENDF/B-IV ($E_\beta+E_\gamma$)	$H_1(t,\infty)$ STUDY ($E_\beta+E_\gamma$)
	([Mev/sec]/[fiss/sec])					
0.	6.471E+00	6.246E+00	6.129E+00	6.859E+00	1.260E+01	1.310E+01
1.00E-01	6.385E+00	6.183E+00	6.063E+00	6.740E+00	1.245E+01	1.292E+01
1.50E-01	6.346E+00	6.154E+00	6.034E+00	6.687E+00	1.238E+01	1.284E+01
2.00E-01	6.309E+00	6.126E+00	6.006E+00	6.639E+00	1.231E+01	1.276E+01
3.00E-01	6.241E+00	6.075E+00	5.955E+00	6.551E+00	1.220E+01	1.263E+01
4.00E-01	6.180E+00	6.027E+00	5.910E+00	6.475E+00	1.209E+01	1.250E+01
6.00E-01	6.074E+00	5.942E+00	5.831E+00	6.345E+00	1.191E+01	1.229E+01
8.00E-01	5.983E+00	5.867E+00	5.764E+00	6.239E+00	1.175E+01	1.211E+01
1.00E+00	5.902E+00	5.799E+00	5.705E+00	6.149E+00	1.161E+01	1.195E+01
1.50E+00	5.733E+00	5.653E+00	5.582E+00	5.966E+00	1.131E+01	1.162E+01
2.00E+00	5.593E+00	5.528E+00	5.481E+00	5.823E+00	1.107E+01	1.135E+01
3.00E+00	5.368E+00	5.323E+00	5.321E+00	5.601E+00	1.069E+01	1.092E+01
4.00E+00	5.189E+00	5.157E+00	5.194E+00	5.431E+00	1.038E+01	1.059E+01
6.00E+00	4.910E+00	4.894E+00	4.998E+00	5.175E+00	9.908E+00	1.007E+01
8.00E+00	4.695E+00	4.688E+00	4.847E+00	4.983E+00	9.542E+00	9.671E+00
1.00E+01	4.520E+00	4.519E+00	4.722E+00	4.829E+00	9.242E+00	9.347E+00
1.50E+01	4.198E+00	4.196E+00	4.478E+00	4.538E+00	8.668E+00	8.734E+00
2.00E+01	3.952E+00	3.963E+00	4.294E+00	4.328E+00	8.247E+00	8.290E+00
3.00E+01	3.627E+00	3.641E+00	4.026E+00	4.032E+00	7.653E+00	7.672E+00
4.00E+01	3.408E+00	3.423E+00	3.832E+00	3.826E+00	7.240E+00	7.249E+00
6.00E+01	3.119E+00	3.133E+00	3.561E+00	3.547E+00	6.680E+00	6.680E+00
8.00E+01	2.928E+00	2.939E+00	3.372E+00	3.358E+00	6.300E+00	6.298E+00
1.00E+02	2.788E+00	2.798E+00	3.230E+00	3.218E+00	6.018E+00	6.015E+00
1.50E+02	2.554E+00	2.560E+00	2.987E+00	2.979E+00	5.540E+00	5.539E+00
2.00E+02	2.404E+00	2.409E+00	2.828E+00	2.824E+00	5.233E+00	5.233E+00
3.00E+02	2.212E+00	2.215E+00	2.627E+00	2.625E+00	4.839E+00	4.480E+00
4.00E+02	2.085E+00	2.087E+00	2.495E+00	2.494E+00	4.580E+00	4.581E+00
6.00E+02	1.911E+00	1.912E+00	2.316E+00	2.315E+00	4.227E+00	4.227E+00
8.00E+02	1.787E+00	1.789E+00	2.188E+00	2.186E+00	3.976E+00	3.976E+00
1.00E+03	1.692E+00	1.694E+00	2.086E+00	2.084E+00	3.778E+00	3.778E+00
1.50E+03	1.520E+00	1.522E+00	1.892E+00	1.890E+00	3.412E+00	3.411E+00
2.00E+03	1.403E+00	1.404E+00	1.748E+00	1.746E+00	3.151E+00	3.150E+00
3.00E+03	1.250E+00	1.251E+00	1.543E+00	1.541E+00	2.793E+00	2.792E+00
4.00E+03	1.153E+00	1.154E+00	1.401E+00	1.400E+00	2.554E+00	2.554E+00
6.00E+03	1.033E+00	1.034E+00	1.214E+00	1.213E+00	2.247E+00	2.247E+00
8.00E+03	9.573E-01	9.579E-01	1.093E+00	1.092E+00	2.051E+00	2.050E+00
1.00E+04	9.020E-01	9.026E-01	1.008E+00	1.007E+00	1.910E+00	1.909E+00

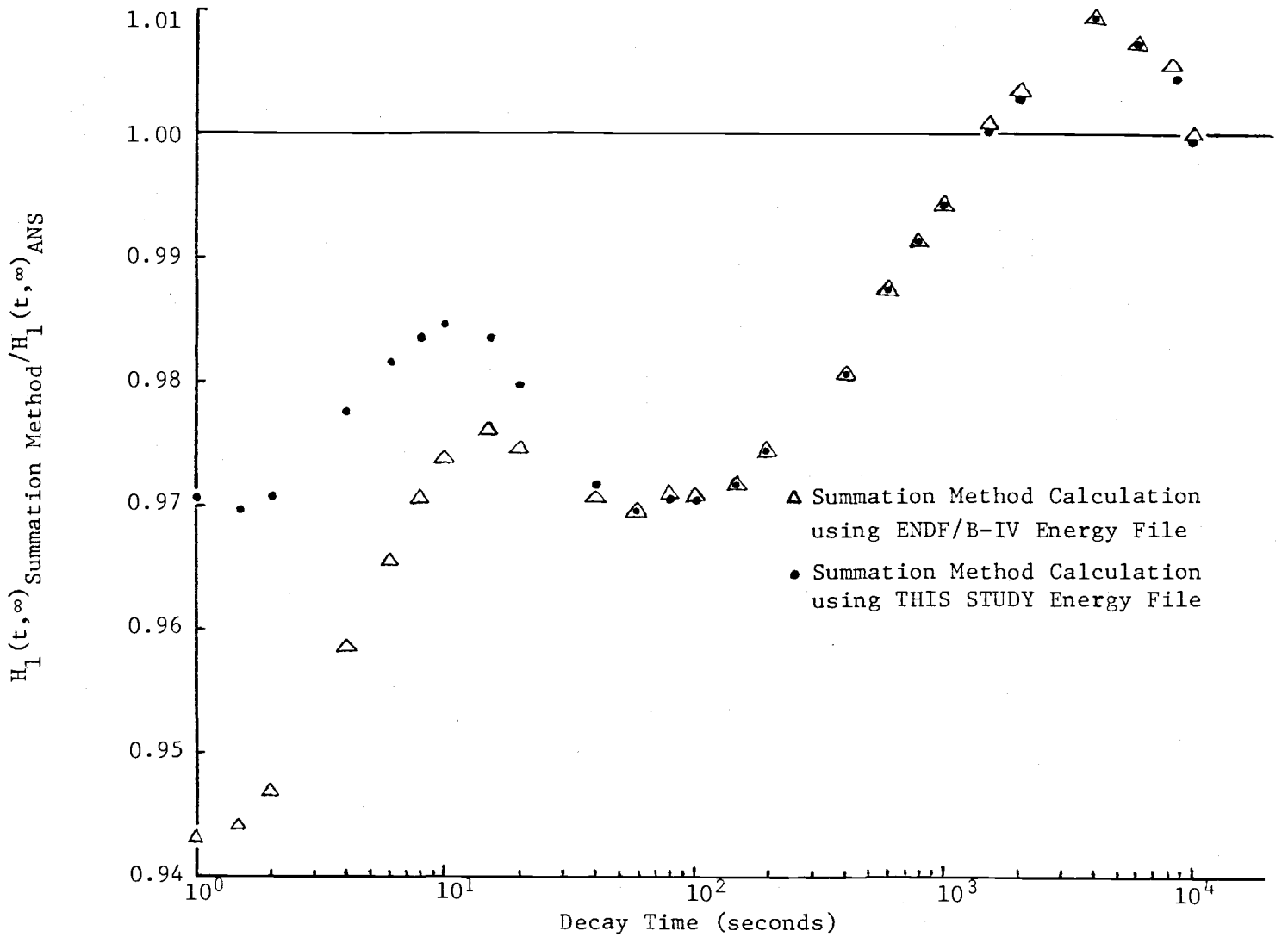

FIGURE 7-5 Ratio of Summation Method to ANS Standard expressed in terms of $H_1(t,\infty)$(decay power).

TABLE 7-5 Total decay energies from ANS, THIS STUDY and ENDF/B-IV expressed in terms of $H_1(t,\infty)$ (infinite irradiation ^{235}U decay power).

Decay time (sec)	$H_1(t,\infty)$ ANS ([M e v / s e c] / [f i s s / s e c]) $(E_\beta+E_\gamma)$	$H_1(t,\infty)$ THIS STUDY $(E_\beta+E_\gamma)$	$H_1(t,\infty)$ ENDF/B-IV $(E_\beta+E_\gamma)$
1.00	12.31	11.95	11.61
1.50	11.98	11.62	11.31
2.00	11.69	11.35	11.07
3.00	---	10.92	10.69
4.00	10.83	10.59	10.38
6.00	10.26	10.07	9.908
8.00	9.83	9.671	9.542
10.00	9.49	9.347	9.242
15.00	8.88	8.734	8.668
20.00	8.46	8.290	8.247
30.00	---	7.672	7.653
40.00	7.46	7.249	7.240
60.00	6.89	6.680	6.680
80.00	6.49	6.298	6.300
100.00	6.20	6.015	6.018
150.00	5.70	5.539	5.540
200.00	5.37	5.233	5.233
300.00	---	4.480	4.839
400.00	4.67	4.581	4.580
600.00	4.28	4.227	4.227
800.00	4.01	3.976	3.976
1000.00	3.80	3.778	3.778
1500.00	3.41	3.411	3.412
2000.00	3.14	3.150	3.151
3000.00	---	2.792	2.793
4000.00	2.53	2.554	2.554
6000.00	2.23	2.247	2.247
8000.00	2.04	2.050	2.051
10000.00	1.91	1.909	1.910

is superior? Therefore, a comparison with the best data available is necessary.

Two organizations, the American Nuclear Society, and the U.S. Nuclear Regulatory Commission, are concerned with the development of standard ways of estimating decay power following reactor shutdown. There are two ways of presenting these estimates: as algorithms for determining "best estimates" and their standard deviations; and as standard curves which can conservatively predict decay power without the degree of conservatism being extreme. Although both ANS and NRC are clearly concerned with both types of "standards", ANS is somewhat more focused on the "best estimate algorithm" approach and NRC on the "conservative curve" approach, as befits the two organizations' primary responsibilities. ANS is most responsible for providing evaluated information, and NRC for public protection regulation. Current version of the ANS Standard[55] and its uncertainty are compiled and evaluated by Schmittroth and Schenter.[56] It is a concatenation of good experimental data and has a precision ranging from ±3.3% at one second decay to better than ±2% beyond 10 seconds of decay time and is considered to be the best estimates of decay-heat available.

Comparisons of summation calculations with respect to ANS Standard between ENDF/B-IV and THIS STUDY were performed and results are shown in Figure 7-5 and are listed in Table 7-5. For short decay times, because of the higher total energies predicted by

this study, summation calculations by using this new decay energy file match the ANS Decay-Heat Standard more closely than ENDF/B-IV. For decay times greater than about 60 seconds, as before, there are no noticeable differences.

VII.3 Uncertainties

ENDF/B-IV gives the average sensible energy released per decay for the fission products, but does not list decay energy uncertainties. However, decay energy uncertainties had been evaluated by Baker.[10] Two sources of error are considered by Baker: a random or uncorrelated error in the decay energies predicted by the model, and a correlated error resulting from a bias in the model which systematically predicted energies too high or too low.

Because of their randomness (proved in chapter VI), the decay energy ($E_\beta + E_\gamma$) uncertainties evaluated in this study are uncorrelated uncertainties as defined above. Uncertainties in $H_o(t)$ and $H_1(t,\infty)$ functions due to uncorrelated uncertainties in the total decay energy from ENDF/B-IV as derived by Baker and THIS STUDY are listed in Table 7-6, which indicates uncertainties from THIS STUDY are smaller than uncertainties from ENDF/B-IV up to decay time of 6,000 seconds for $H_o(t)$ and 3,000 seconds for $H_1(t,\infty)$.

TABLE 7-6 Uncorrelated energy uncertainties in $H_o(t)$ and $H_1(t,\infty)$ functions.

Decay time (sec)	Uncorrelated energy uncertainties in $H_o(t)$		in $H_1(t,\infty)$	
	(ENDF/B-IV)	(STUDY)	(ENDF/B-IV)	(STUDY)
0.	.179E+00	.120E+00	.031E+01	.020E+01
1.00E-01	.140E+00	.095E+00	.031E+01	.020E+01
1.50E-01	.125E+00	.084E+00	.031E+01	.020E+01
2.00E-01	.112E+00	.076E+00	.030E+01	.020E+01
3.00E-01	.091E+00	.062E+00	.030E+01	.019E+01
4.00E-01	.076E+00	.051E+00	.030E+01	.019E+01
6.00E-01	.558E-01	.373E-01	.029E+01	.019E+01
8.00E-01	.444E-01	.293E-01	.029E+01	.018E+01
1.00E+00	.375E-01	.244E-01	.028E+01	.018E+01
1.50E+00	.281E-01	.181E-01	.028E+01	.018E+01
2.00E+00	.232E-01	.150E-01	.027E+01	.017E+01
3.00E+00	.175E-01	.115E-01	.026E+01	.016E+01
4.00E+00	.142E-01	.096E-01	.025E+01	.016E+01
6.00E+00	.107E-01	.073E-01	.232E+00	.015E+01
8.00E+00	.088E-01	.060E-01	.218E+00	.138E+00
1.00E+01	.075E-01	.051E-01	.206E+00	.131E+00
1.50E+01	.554E-02	.036E-01	.183E+00	.117E+00
2.00E+01	.429E-02	.270E-02	.166E+00	.106E+00
3.00E+01	.281E-02	.168E-02	.141E+00	.093E+00
4.00E+01	.200E-02	.117E-02	.125E+00	.085E+00
6.00E+01	.118E-02	.069E-02	.106E+00	.075E+00
8.00E+01	.077E-02	.046E-02	.096E+00	.069E+00
1.00E+02	.053E-02	.033E-02	.089E+00	.065E+00
1.50E+02	.242E-03	.165E-03	.081E+00	.060E+00
2.00E+02	.141E-03	.100E-03	.077E+00	.058E+00
3.00E+02	.072E-03	.053E-03	.072E+00	.054E+00
4.00E+02	.053E-03	.038E-03	.067E+00	.052E+00
6.00E+02	.040E-03	.026E-03	.061E+00	.049E+00
8.00E+02	.032E-03	.020E-03	.055E+00	.046E+00
1.00E+03	.272E-04	.166E-04	.051E+00	.044E+00
1.50E+03	.179E-04	.109E-04	.044E+00	.041E+00
2.00E+03	.121E-04	.076E-04	.041E+00	.039E+00
3.00E+03	.060E-04	.043E-04	.037E+00	.036E+00
4.00E+03	.035E-04	.030E-04	.035E+00	.035E+00
6.00E+03	.020E-04	.019E-04	.032E+00	.032E+00
8.00E+03	.143E-05	.143E-05	.031E+00	.031E+00
1.00E+04	.110E-05	.110E-05	.029E+00	.029E+00

VIII. CONCLUSIONS

Even though it is tedious, theoretical predictions of average beta and gamma decay energies are clearly feasible. Conclusions, which can be drawn from the comparisons discussed in last chapter, are that: decay-heat calculated by using results of this study ($E_\beta + E_\gamma$) compared better than the existing ENDF/B-IV with the ANS Decay-Heat Standard: and uncertainties in the $H_o(t)$ and $H_1(t,\infty)$ functions from the uncertainties of the total decay energy derived from this study are smaller than those previously obtained.[57]

According to Schmittroth's and Schenter's[9] studies on the uncertainties in fission-product decay-heat calculations, the main sources of uncertainty in decay-heat summation calculations are due to fission yields and decay energies; for the thermal fission of ^{235}U, where fission yields have been extensively studied, decay energies are the major source of decay-heat error, especially for the very short cooling times (less than 100 seconds). Therefore, they recommanded that for ^{235}U, future work on ENDF/B should be directed towards obtaining more accurate decay energies. From the comparisons discussed in last chapter, decay energies, predicted by this study, seem to be a step closer in fulfilling the recommandation suggested by Schmittroth and Schenter. Therefore, results of this study are recommanded for use in future theoretical evaluation of decay heat for those isotope for which good experimental values are not available. The improvement noted by using

the results of this work suggests that, where such experimental data are lacking, our decay energy predictions are a significant improvement over those used in the ENDF compilations.

Although decent results were obtained, there is still room for improvement. Three areas can be immediately mentioned:

1). Internal conversion - nuclear de-excitation by ejecting an atomic electron instead of gamma emission. This effect can increase theoretical average beta decay energies and at the same time decrease average gamma decay energies. This effect may improve the comparison as indicated in Figure 7-2.

2). Deformed nuclei - deformed nuclei are assumed to be spherical in this study due to their small fission yields. But models[58] as well as level density formula[59] are available for deformed nuclei, so they could be treated more precisely.

3). Parity partition in level density - equal probability between positive and negative parities is assumed, but the decay level diagram of ^{88}Rb[60] shows 1^+ states located at high energy and 1^- states located at relative low energy in the continuum. As a result, the calculated gamma decay energy is low when compared to experiment. However, parity dependent level density formulae are not available.

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APPENDICES

Appendix I

PARAMETER S_c

S_c is defined as f_1/f_o by Equation (5.7) and is a function of charge (Z) and energy (E_x). For any Z, a least-squares fit to a quadratic function of E_x was performed by using values from reference (45). Therefore,

$$S_c(Z) = B_o + B_1E_x + B_2E_x^2 .$$

B_o, B_1, B_2 are listed on next page.

Z	B_o	B_1	B_2
24	-.1104E-01	.1369E+00	.1868E+00
25	-.1060E-01	.1353E+00	.1871E+00
26	-.1032E-01	.1340E+00	.1873E+00
27	-.1004E-01	.1327E+00	.1875E+00
28	-.9753E-02	.1314E+00	.1876E+00
29	-.9470E-02	.1301E+00	.1878E+00
30	-.9187E-02	.1288E+00	.1880E+00
31	-.8824E-02	.1272E+00	.1882E+00
32	-.8462E-02	.1256E+00	.1885E+00
33	-.7943E-02	.1240E+00	.1888E+00
34	-.7737E-02	.1224E+00	.1890E+00
35	-.7374E-02	.1207E+00	.1893E+00
36	-.7061E-02	.1195E+00	.1895E+00
37	-.6748E-02	.1182E+00	.1897E+00
38	-.6435E-02	.1170E+00	.1898E+00
39	-.6122E-02	.1157E+00	.1900E+00
40	-.5808E-02	.1145E+00	.1902E+00
41	-.5753E-02	.1138E+00	.1903E+00
42	-.5698E-02	.1131E+00	.1905E+00
43	-.5644E-02	.1124E+00	.1906E+00
44	-.5589E-02	.1117E+00	.1907E+00
45	-.5534E-02	.1110E+00	.1909E+00
46	-.5571E-02	.1106E+00	.1909E+00
47	-.5608E-02	.1103E+00	.1910E+00
48	-.5645E-02	.1099E+00	.1910E+00
49	-.5683E-02	.1096E+00	.1911E+00
50	-.5720E-02	.1092E+00	.1911E+00
51	-.5118E-02	.1075E+00	.1915E+00
52	-.4515E-02	.1058E+00	.1918E+00
53	-.3913E-02	.1040E+00	.1921E+00
54	-.3311E-02	.1023E+00	.1924E+00
55	-.2709E-02	.1005E+00	.1927E+00
56	-.2479E-02	.9967E-01	.1929E+00
57	-.2249E-02	.9880E-01	.1931E+00
58	-.2019E-02	.9792E-01	.1933E+00
59	-.1790E-02	.9704E-01	.1935E+00
60	-.1560E-02	.9617E-01	.1937E+00
61	-.1312E-02	.9523E-01	.1939E+00
62	-.1065E-02	.9430E-01	.1941E+00
63	-.8174E-03	.9336E-01	.1944E+00
64	-.5699E-03	.9243E-01	.1946E+00
65	-.3225E-03	.9149E-01	.1948E+00
66	-.3821E-04	.9056E-01	.1950E+00
67	.2460E-03	.8963E-01	.1952E+00
68	.5303E-03	.8870E-01	.1954E+00
69	-.3373E-02	.9859E-01	.1928E+00
70	.1099E-02	.8684E-01	.1958E+00

Appendix II

A_o, A_1, A_2 VALUES

According to England,[18, 46, 47] A_o, A_1, A_2, are used to simplify the function G(Z,W) as

$$G(Z,W)\sqrt{W^2 - 1}(2R/\lambda_c)^{-2s} \simeq A_o(Z) + A_1(Z)Z + A_2(Z)W^2$$

where G(Z,W) = electron density ratio,

W = total beta relativistic energy,

R = nuclear radius,

$\lambda_c = \hbar/m_o c = 3.86\times10^{-13}$cm = the rationalized Compton wavelength an electron,

$s = \sqrt{1-(\alpha Z)^2} - 1$,

$\alpha = e^2/\hbar c = 1/137$ = fine structure constant.

Z	A_o	A_1	A_2
24	-.7971E+00	.2054E+01	-.3714E-01
25	-.7549E+00	.2070E+01	-.3583E-01
26	-.7150E+00	.2089E+01	-.3492E-01
27	-.6747E+00	.2110E+01	-.3411E-01
28	-.6343E+00	.2131E+01	-.3340E-01
29	-.5935E+00	.2154E+01	-.3279E-01
30	-.5525E+00	.2178E+01	-.3231E-01
31	-.5109E+00	.2202E+01	-.3193E-01
32	-.4679E+00	.2227E+01	-.3153E-01
33	-.4254E+00	.2254E+01	-.3138E-01
34	-.3823E+00	.2282E+01	-.3132E-01
35	-.3384E+00	.2311E+01	-.3137E-01
36	-.2938E+00	.2340E+01	-.3152E-01
37	-.2483E+00	.2371E+01	-.3176E-01
38	-.2019E+00	.2402E+01	-.3211E-01
39	-.1546E+00	.2435E+01	-.3256E-01
40	-.1061E+00	.2468E+01	-.3311E-01
41	-.5657E-01	.2501E+01	-.3376E-01
42	-.5782E-01	.2536E+01	-.3451E-01
43	.4630E-01	.2571E+01	-.3576E-01
44	.9978E-01	.2607E+01	-.3631E-01
45	.1547E+00	.2644E+01	-.3735E-01
46	.2112E+00	.2681E+01	-.3850E-01
47	.2694E+00	.2719E+01	-.3974E-01
48	.3293E+00	.2758E+01	-.4108E-01
49	.3910E+00	.2797E+01	-.4252E-01
50	.4547E+00	.2836E+01	-.4405E-01
51	.5205E+00	.2876E+01	-.4567E-01
52	.5883E+00	.2916E+01	-.4739E-01
53	.6585E+00	.2957E+01	-.4920E-01
54	.7311E+00	.2997E+01	-.5110E-01
55	.8058E+00	.3038E+01	-.5307E-01
56	.8835E+00	.3079E+01	-.5515E-01
57	.9641E+00	.3121E+01	-.5731E-01
58	.1047E+01	.3162E+01	-.5956E-01
59	.1134E+01	.3203E+01	-.6188E-01
60	.1224E+01	.3244E+01	-.6428E-01
61	.1317E+01	.3285E+01	-.6676E-01
62	.1413E+01	.3326E+01	-.6930E-01
63	.1513E+01	.3366E+01	-.7191E-01
64	.1617E+01	.3405E+01	-.7459E-01
65	.1725E+01	.3445E+01	-.7732E-01
66	.1837E+01	.3483E+01	-.8010E-01
67	.1953E+01	.3521E+01	-.8394E-01
68	.2074E+01	.3558E+01	-.8581E-01
69	.2200E+01	.3593E+01	-.8872E-01
70	.2330E+01	.3628E+01	-.9166E-01

Appendix III

A TABULATION OF FISSION PRODUCT DECAY ENERGIES

This is a file of decay energies for those nuclides which might contribute to reactor decay heat. The column headed "NUCLIDE" identifies the nuclides for which data is displayed. Each nuclide identifier is a six digit integer; the first three digits give the atomic mass number, the next two digits give the atomic charge number, and the last digit indicates the metastable state. The column headed "E BETA", "E GAMMA", and "TOTAL" give the beta, gamma, and total ($E_\beta + E_\gamma$) energy of decay. The column headed "UNC TOTAL" gives the total energy uncertainties (see TABLE 6-2).

An asterisk following a nuclide identifier indicates that the energy data for that nuclide was obtained experimentally. Two asterisks following a nuclide identifier indicate that the energy data for that nuclide was obtained from reference (10). There are two reasons for using values from reference (10): one, the treatment of metastable states has already been mentioned in section V.3, the other is that for certain nuclides such as: 73310, 83350, 87370, 93400, 113480, 115480, 115490, 117490, 129530, 135550, their beta decay modes are of second forbidden or higher order, decay modes which were not treated explicitly in this study.

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
66240	2.5436	5.8761	8.4198	1.7958
66250	2.2658	9.5517	11.8175	2.2816
66260	1.9028	1.9400	3.8428	.9700
66270	3.2433	2.3810	5.6243	1.4777
66280	.0679	0.0000	.0679	.0370
66290	1.0810	.0859	1.1669	.4139
66300	0.0000	0.0000	0.0000	0.0000
67240	2.5474	9.5920	12.1394	2.3787
67250	2.3690	7.3507	9.7198	1.9697
67260	2.1007	5.3018	7.4025	1.5623
67270	1.5901	3.8721	5.4622	1.1721
67280	1.6020	.1940	1.7960	.6002
67290	.1879	.0009	.1889	.0901
67300	0.0000	0.0000	0.0000	0.0000
68240	2.6689	7.2259	9.8949	2.0481
68250	2.3901	11.0137	13.4038	2.5511
68260	2.2383	3.0189	5.2572	1.2489
68270	2.0441	6.7059	8.7499	1.7644
68280	.8941	.0630	.9572	.3479
68291	.5514	1.7466	2.2980	.8370
68290	1.8940	.3756	2.2696	.7240
68300	0.0000	0.0000	0.0000	0.0000
69250	2.5351	8.6163	11.1514	2.2220
69260	2.2533	6.6943	8.9475	1.8303
69270	2.1013	4.5887	6.6900	1.4510
69280	1.4609	2.6728	4.1337	.9418
69290	1.0431	.0026	1.0457	.3886
69301	0.0000	.4386	.4386	0.0000
69300	.3209	0.0000	.3209	.1417
69310	0.0000	0.0000	0.0000	0.0000
70240	2.8194	8.4520	11.2714	2.2894
70250	2.5482	12.0284	14.5766	2.7811
70260	2.4311	4.2160	6.6471	1.4996
70270	2.3789	7.7235	10.1024	2.0340
70280	1.2241	1.1575	2.3816	.6268
70291	1.5752	2.5956	4.1708	.9668
70290	1.4785	2.8077	4.2862	.9668
70300	0.0000	0.0000	0.0000	0.0000
71250	2.7127	9.7765	12.4893	2.4618
71260	2.4123	7.7179	10.1302	2.0418
71270	2.2898	5.7982	8.0881	1.7018
71280	1.8118	3.6581	5.4699	1.2113
71290	1.9034	.2669	2.1702	.7099
71301	.9069	.8287	1.7356	.4662
71300	1.1550	.1033	1.2583	.4416
71310	0.0000	0.0000	0.0000	0.0000
72260	2.6107	5.3914	8.0022	1.7425
72270	2.2927	9.2421	11.5348	2.2424
72280	1.7377	1.6961	3.4338	.8791
72290	2.0196	3.7627	5.7823	1.2943
72300	.1539	.0414	.1953	.0716

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
72310	1.0743	1.4805	2.5548	.6255
72320	0.0000	0.0000	0.0000	0.0000
73260	2.6129	8.7108	11.3236	2.2627
73270	2.4948	6.9132	9.4080	1.9431
73280	1.9202	4.7621	6.6822	1.4197
73290	1.3479	3.0363	4.3842	.9637
73300	1.3653	1.5732	2.9384	.7365
73310**	.4440	.3190	.7630	.3495
73321	0.0000	.0667	.0667	0.0000
73320	0.0000	0.0000	0.0000	0.0000
74260	2.8740	6.2002	9.0742	1.9556
74270	2.3889	10.0512	12.6401	2.4665
74280	2.1179	2.4342	4.5520	1.1188
74290	1.9549	5.2265	7.1813	1.5043
74300	.5569	.9146	1.4715	.3682
74310	1.6309	1.7112	3.3421	.8462
74320	0.0000	0.0000	0.0000	0.0000
75270	2.7733	7.7128	10.4861	2.1593
75280	2.1622	5.6693	7.8315	1.6406
75290	1.7098	3.8259	5.5357	1.2050
75300	1.3791	2.9229	4.3020	.9559
75310	1.4198	.0296	1.4493	.5171
75321	0.0000	.1393	.1393	0.0000
75320	.4365	.0002	.4367	.1846
75330	0.0000	0.0000	0.0000	0.0000
76260	3.3200	6.6572	9.9773	2.1750
76270	2.9524	10.7067	13.6591	2.6890
76280	2.4901	3.0379	5.5280	1.3351
76290	2.2929	5.9311	8.2241	1.7253
76300	1.1785	1.1335	2.3120	.6096
76310	2.0298	2.2455	4.2754	1.0609
76320	0.0000	0.0000	0.0000	0.0000
77280	2.5070	6.3820	8.8890	1.8647
77290	2.0214	4.5512	6.5726	1.4197
77300	1.6548	3.7462	5.4010	1.1753
77310	1.2653	1.8639	3.1292	.7522
77321	.9223	.1224	1.0447	.4484
77320	1.0891	.1593	1.2483	.4233
77330	.2311	0.0000	.2311	.1082
77341	0.0000	.1620	.1620	0.0000
77340	0.0000	0.0000	0.0000	0.0000
78280	3.0001	3.3493	6.3493	1.5513
78290	2.7046	6.4990	9.2035	1.9493
78300	1.7330	1.6876	3.4206	.8775
78310	1.9813	3.6543	5.6355	1.2661
78320	.2518	.2939	.5457	.1536
78330	1.5985	.6677	2.2663	.6722
78340	0.0000	0.0000	0.0000	0.0000
79290	2.3796	5.1996	7.5792	1.6375
79300	1.9452	4.3024	6.2476	1.3570
79310	2.5578	1.1313	3.6891	1.0593

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
79320*	1.8927	.2314	2.1441	.2927
79330	.9245	.0023	.9269	.3447
79341	0.0000	.0959	.0959	0.0000
79340	.0555	0.0000	.0555	.0233
79351	0.0000	.2072	.2072	0.0000
79350	0.0000	0.0000	0.0000	0.0000
80280	3.7455	5.7407	9.4862	2.1734
80290	3.9777	6.7156	10.6933	2.4053
80300	2.1284	1.9367	4.0651	1.0452
80310	2.3178	4.7656	7.0835	1.5513
80320	1.0488	.1319	1.1808	.4121
80330*	2.5226	.6066	3.1292	.3702
80340	0.0000	0.0000	0.0000	0.0000
81290	3.5252	6.7474	10.2726	2.2580
81300	3.0328	4.9539	7.9867	1.8146
81310	1.6089	3.7766	5.3855	1.1658
81320	1.4514	2.9638	4.4152	.9872
81330*	1.6694	0.0000	1.6694	.2220
81341	0.0000	.1029	.1029	0.0000
81340	.6124	.0099	.6223	.2484
81350	0.0000	0.0000	0.0000	0.0000
82280	3.4801	7.6823	11.1624	2.3881
82290	3.4382	9.2251	12.6633	2.6169
82300	3.0811	3.9055	6.9866	1.6657
82310	3.3516	5.0498	8.4014	1.9352
82320	1.7989	.3421	2.1410	.6895
82331*	1.8192	2.9947	4.8139	.4967
82330*	3.2109	.2881	3.4990	.3496
82340	0.0000	0.0000	0.0000	0.0000
83300	2.9453	6.4834	9.4287	2.0246
83310	2.9236	5.0080	7.9315	1.7879
83320	2.2785	3.4330	5.7116	1.3304
83330	1.5192	1.9844	3.5036	.8556
83341*	1.3017	.9093	2.2110	.1715
83340*	.4419	2.5593	3.0012	.1089
83350**	.3240	.0073	.3313	.1085
83361	0.0000	.0416	.0416	0.0000
83360	0.0000	0.0000	0.0000	0.0000
84300	2.9626	5.5155	8.4782	1.8788
84310	2.9435	7.2671	10.2107	2.1484
84320	2.4285	2.1746	4.6031	1.1815
84330	3.6025	1.9563	5.5588	1.5325
84340*	.5308	.4077	.9385	.0793
84351*	.8955	2.7684	3.6639	.2499
84350*	1.2557	1.7527	3.0084	.2614
84360	0.0000	0.0000	0.0000	0.0000
85310	2.7443	6.7474	9.4917	2.0011
85320	2.3348	4.6676	7.0024	1.5419
85330	2.4238	3.6854	6.1092	1.4181
85341**	2.1463	1.3478	3.4941	1.8746
85340	1.6224	2.3991	4.0216	.9559

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
85330*	.9947	.0647	1.0596	.2256
85361*	.2261	.1832	.4093	.0114
85360*	.2506	.0022	.2528	.0023
85370	0.0000	0.0000	0.0000	0.0000
86300	2.7850	7.0310	9.8159	2.0575
86310	2.7228	9.0818	11.8045	2.3599
86320	2.4898	3.4146	5.9044	1.3962
86330	3.3911	3.9564	7.3476	1.7785
86340	1.6873	1.2687	2.9560	.7992
86351**	3.0855	1.6661	4.7516	2.0704
86350*	1.7752	3.3179	5.0931	.3938
86360	0.0000	0.0000	0.0000	0.0000
87320	2.2943	6.1125	8.4068	1.7550
87330	2.3354	5.2298	7.5652	1.6312
87340	1.8779	3.0372	4.9151	1.1392
87350*	2.1356	1.7263	3.8619	.5317
87360*	1.3345	.7926	2.1271	.0768
87370**	.0922	.0486	.1408	.0611
87381	0.0000	.3884	.3884	0.0000
87380	0.0000	0.0000	0.0000	0.0000
88320	2.3480	4.8401	7.1881	1.5733
88330	3.0309	6.0663	9.0972	1.9917
88340	1.9670	1.9148	3.8819	.9919
88350	2.4862	3.0992	5.5854	1.3476
88360*	.2486	2.2118	2.4604	.0904
88370*	2.0826	.6739	2.7565	.1579
88380	0.0000	0.0000	0.0000	0.0000
89330	2.2286	6.5942	8.8228	1.8099
89340	1.9446	4.2578	6.2023	1.3523
89350	1.9387	3.6757	5.6144	1.2599
89360*	1.2412	2.0631	3.3043	.1749
89370*	.9293	2.2890	3.2183	.1833
89380*	.5820	0.0000	.5820	.0344
89391	0.0000	.9092	.9092	0.0000
89390	0.0000	0.0000	0.0000	0.0000
90340	2.0099	2.9636	4.9734	1.1705
90350	2.7588	4.2545	7.0133	1.6187
90360*	1.1870	1.7491	2.9361	.1860
90371*	1.1063	3.6160	4.7223	.4720
90370*	1.6586	2.6604	4.3190	.5841
90380*	.1980	0.0000	.1980	.0312
90391*	.0009	.6825	.6834	.0548
90390*	.9310	.0003	.9313	.0564
90401*	0.0000	2.3148	2.3148	.2362
90400	0.0000	0.0000	0.0000	0.0000
91340	1.9428	5.9426	7.8854	1.6156
91350	1.8997	4.8966	6.7963	1.4385
91360*	2.5778	.7236	3.3014	.4100
91370*	1.3342	2.7332	4.0674	.5658
91380*	.6523	.6954	1.3477	.2086
91391*	0.0000	.5552	.5552	.0585

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
91390*	.6060	.0027	.6087	.1083
91400	0.0000	0.0000	0.0000	0.0000
92340	2.0221	4.1977	6.2198	1.3680
92350	2.2435	7.0105	9.2539	1.8820
92360*	2.4032	.7518	3.1550	.2741
92370*	3.4593	.2614	3.7207	.2816
92380*	.1923	1.3388	1.5311	.0842
92390*	1.4642	.2482	1.7124	.3036
92400	0.0000	0.0000	0.0000	0.0000
93350	1.9375	6.0694	8.0069	1.6344
93360	1.5935	4.3473	5.9408	1.2536
93370	1.6596	3.5665	5.2261	1.1533
93380*	1.1611	1.3950	2.5561	.2972
93390*	1.1845	.0896	1.2741	.0338
93400**	.0125	.0074	.0199	.0088
93411	0.0000	.0304	.0304	0.0000
93410	0.0000	0.0000	0.0000	0.0000
94340	2.0055	5.3929	7.3984	1.5498
94350	2.0092	8.8014	10.8107	2.0857
94360	1.6701	2.7493	4.4194	1.0280
94370	1.6694	5.6859	7.3553	1.4887
94380*	.8696	1.2425	2.1121	.2256
94390*	1.7174	.9861	2.7035	.3048
94400	0.0000	0.0000	0.0000	0.0000
95360	1.7397	5.4945	7.2342	1.4808
95370	1.6842	4.7448	6.4290	1.3461
95380	1.1726	3.3058	4.4783	.9543
95390*	1.7457	.4883	2.2340	.3024
95400*	.1163	.7361	.8524	.0239
95411*	0.0000	.2355	.2355	.0871
95410*	.0436	.7658	.8094	.0835
95420	0.0000	0.0000	0.0000	0.0000
96340	2.0134	6.4072	8.4205	1.7112
96350	2.0500	10.0674	12.1174	2.2972
96360	1.7179	3.8095	5.5274	1.2097
96370	1.6214	6.5851	8.2065	1.6140
96380	1.4719	1.9538	3.4256	.8399
96390	1.9259	2.6716	4.5975	1.1000
96400	0.0000	0.0000	0.0000	0.0000
97360	1.7956	6.7289	8.5245	1.6924
97370	1.6556	5.2742	6.9298	1.4197
97380	1.4023	3.9361	5.3384	1.1282
97390*	2.1621	.9350	3.0971	.3124
97400*	.7071	.1818	.8889	.1604
97411*	0.0000	.7427	.7427	.0740
97410*	.4679	.6770	1.1449	.1563
97420	0.0000	0.0000	0.0000	0.0000
98360	1.7393	4.7952	6.5345	1.3711
98370	1.7445	8.1401	9.8846	1.8976
98380	1.4780	2.3900	3.8680	.9104
98390	1.5783	4.4680	6.0463	1.2693

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
98400	.8486	.1368	.9855	.3509
98411*	.8481	2.5150	3.3631	.3147
98410*	1.8653	.1402	2.0055	.2417
98420	0.0000	0.0000	0.0000	0.0000
99380	1.4917	5.0002	6.4919	1.3241
99390	1.2861	3.3650	4.6511	1.0013
99400*	1.6205	.7937	2.4142	.2767
99411*	.9537	1.9943	2.9480	.3594
99410*	1.5225	.1997	1.7222	.2481
99420*	.3847	.1861	.5708	.0135
99431*	0.0000	.1427	.1427	.0154
99430	.0070	.2659	.2729	.0460
99440	0.0000	0.0000	0.0000	0.0000
100360	1.8155	5.8276	7.6431	1.5576
100370	1.8122	9.0802	10.8923	2.0669
100380	1.4759	2.9835	4.4594	1.0029
100390	1.5898	5.9322	7.5221	1.5028
100400	1.2458	.4192	1.6650	.5265
100411**	2.1186	1.3656	3.4842	1.5656
100410*	2.0596	1.9205	3.9901	.3165
100420	0.0000	0.0000	0.0000	0.0000
101380	1.5868	5.8828	7.4695	1.4934
101390	1.4082	4.2697	5.6780	1.1831
101400	1.6645	2.0893	3.7538	.9245
101410*	1.9006	.3300	2.2306	.2794
101420*	.5950	1.3862	1.9812	.0506
101430*	.4800	.3363	.8163	.0488
101440	0.0000	0.0000	0.0000	0.0000
102380	1.5675	3.9827	5.5502	1.1894
102390	1.6012	6.9882	8.5894	1.6720
102400	1.2937	.6597	1.9534	.5798
102410	2.6658	1.3050	3.9708	1.1282
102420*	.3111	0.0000	.3111	.0578
102431*	.7195	2.5466	3.2661	.3309
102430*	1.5088	.4633	1.9721	.2754
102440	0.0000	0.0000	0.0000	0.0000
103390	1.5171	5.2231	6.7402	1.3680
103400	1.4440	3.4646	4.9085	1.0687
103410	1.7734	1.1606	2.9340	.8148
103420	1.6948	.4205	2.1153	.6738
103430	.8343	.2653	1.0997	.3682
103440*	.0675	.4900	.5575	.0649
103451*	0.0000	.0398	.0398	.0040
103450	0.0000	0.0000	0.0000	0.0000
104380	1.6801	5.1191	6.7992	1.4040
104390	1.7626	7.7929	9.5555	1.8506
104400	1.4216	1.5718	2.9934	.7647
104410	2.5120	2.9317	5.4437	1.3335
104420	.6065	.6268	1.2333	.3447
104430*	1.1930	1.4481	2.6411	.3934
104440	0.0000	0.0000	0.0000	0.0000

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
105400	1.4004	4.7117	6.1121	1.2505
105410	1.4548	3.1898	4.6446	1.0295
105420	1.6611	1.5932	3.2543	.8462
105430	.4896	2.0766	2.5661	.5328
105440*	.4126	.7877	1.2003	.0272
105451*	0.0000	.1297	.1297	.0478
105450*	.1523	.0788	.2311	.0322
105460	0.0000	0.0000	0.0000	0.0000
106400	1.3548	3.0773	4.4321	.9794
106410	1.5240	6.1315	7.6554	1.5137
106420	1.1233	.4227	1.5461	.4873
106430	2.3994	.9459	3.3452	.9872
106440*	.0100	0.0000	.0100	.0016
106451*	.3487	2.6452	2.9939	.2328
106450*	1.4457	.1994	1.6451	.2454
106460	0.0000	0.0000	0.0000	0.0000
107410	1.3015	4.8739	6.1755	1.2442
107420	1.1648	3.4104	4.5752	.9700
107430	1.6696	.3638	2.0334	.6581
107440*	1.2375	.2514	1.4889	.2605
107450*	.4212	.3123	.7335	.1038
107461	0.0000	.2140	.2140	0.0000
107460	.0129	0.0000	.0129	.0052
107471	0.0000	.0931	.0931	0.0000
107470	0.0000	0.0000	0.0000	0.0000
108400	1.4637	3.9900	5.4537	1.1580
108410	1.6245	7.1113	8.7358	1.7002
108420	1.1338	1.7682	2.9020	.7020
108430	1.6645	4.1644	5.8289	1.2520
108440*	.4701	.0462	.5163	.0980
108451*	.8041	2.4395	3.2436	.3078
108450*	1.8281	.7085	2.5366	.3405
108460	0.0000	0.0000	0.0000	0.0000
109410	1.4364	5.7325	7.1689	1.4228
109420	1.2831	4.3623	5.6454	1.1580
109430	1.0630	3.7075	4.7705	.9841
109440	.8009	2.2843	3.0852	.6738
109451**	0.0000	.2500	.2500	.6530
109450	.9021	.2637	1.1658	.3918
109461*	0.0000	.1880	.1880	.0184
109460*	.3641	.0002	.3643	.0685
109471*	0.0000	.0877	.0877	.0088
109470	0.0000	0.0000	0.0000	0.0000
110400	1.5934	4.7902	6.3836	1.3257
110410	1.6987	8.0771	9.7758	1.8757
110420	1.2817	2.5963	3.8780	.8807
110430	1.8170	5.0421	6.8591	1.4401
110440	.7094	.7791	1.4885	.4059
110451*	2.4812	.0561	2.5373	.2839
110450*	1.3457	2.2677	3.6134	.3542
110460	0.0000	0.0000	0.0000	0.0000

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
111420	1.4477	5.1388	6.5865	1.3335
111430	1.2249	4.4964	5.7213	1.1611
111440	.9902	3.0886	4.0788	.8634
111450	1.3243	.3735	1.6977	.5485
111461*	.1671	.4214	.5885	.0442
111460*	.8442	.0529	.8971	.0641
111471*	0.0000	.0650	.0650	.0064
111470*	.3548	.0270	.3818	.0821
111481	0.0000	.3960	.3960	0.0000
111480	0.0000	0.0000	0.0000	0.0000
112420	1.4243	3.3679	4.7922	1.0483
112430	1.6349	6.5305	8.1654	1.6140
112440	.9816	1.3305	2.3121	.5845
112450	2.2157	1.9591	4.1748	1.0875
112460	.0983	.0213	.1197	.0459
112470*	1.4289	.6638	2.0927	.2883
112480	0.0000	0.0000	0.0000	0.0000
113430	1.3804	5.2406	6.6211	1.3288
113440	1.1937	3.7682	4.9619	1.0374
113450	.8571	3.0204	3.8775	.8086
113460	.7865	1.4348	2.2213	.5328
113471**	.6495	.5313	1.1808	.5532
113470	.7921	.0492	.8414	.3150
113481	.2120	.0003	.2123	.0918
113480**	0.0000	0.0000	0.0000	0.0000
113491	0.0000	.3917	.3917	0.0000
113490	0.0000	0.0000	0.0000	0.0000
114420	1.5630	4.1289	5.6918	1.2129
114430	1.4406	8.0249	9.4655	1.7848
114440	1.1785	1.9723	3.1508	.7506
114450	2.0021	3.5128	5.5149	1.2614
114460	.6233	.1115	.7347	.2727
114470	1.8454	.6354	2.4808	.7616
114480	0.0000	0.0000	0.0000	0.0000
115440	1.2722	4.6836	5.9558	1.2066
115450	1.0499	3.6785	4.7284	.9762
115460	.9484	2.2860	3.2344	.7240
115471**	1.0153	.8926	1.9079	1.0486
115470	1.0317	.6940	1.7257	.4983
115481	.6390	0.0000	.6390	.2540
115480**	.3172	.2656	.5828	.2742
115491	.0109	.3249	.3358	.1302
115490**	.1343	.1076	.2419	.1129
115500	0.0000	0.0000	0.0000	0.0000
116420	1.7367	4.6079	6.3446	1.3445
116430	1.5952	8.8128	10.4080	1.9588
116440	1.3424	2.6773	4.0197	.9151
116450	1.1505	6.3761	7.5266	1.4322
116460	.7687	.8538	1.6226	.4388
116471**	1.9617	1.5947	3.5564	1.6643
116470	2.0751	1.3988	3.4738	.9559

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
116480	0.0000	0.0000	0.0000	0.0000
117440	1.4367	5.4592	6.8959	1.3821
117450	1.2468	4.3031	5.5500	1.1392
117460	1.0375	3.1943	4.2319	.8963
117471**	1.3408	1.2591	2.5999	1.6591
117470	.6612	2.4618	3.1230	.6550
117481**	.7157	.6553	1.3710	.8318
117480	.3024	1.6388	1.9412	.3961
117491**	.2621	.3745	.6366	.3274
117490**	.4074	.3529	.7603	.3598
117500	0.0000	0.0000	0.0000	0.0000
118440	1.5264	3.1423	4.6687	1.0483
118450	1.3385	7.0909	8.4293	1.6062
118460	1.0356	1.3290	2.3646	.6033
118471**	1.2957	1.2285	2.5242	1.6325
118470	.9656	4.8577	5.8233	1.1329
118480	.2425	.0135	.2560	.1175
118491*	1.7758	.2181	1.9939	.3063
118490*	.6295	2.5759	3.2054	.2764
118500	0.0000	0.0000	0.0000	0.0000
119440	1.6287	5.8790	7.5077	1.5106
119450	1.4202	4.7893	6.2096	1.2724
119460	1.2153	3.9267	5.1420	1.0703
119470	1.0355	2.8374	3.8728	.8399
119481**	1.0485	1.0152	2.0637	1.1352
119480	.9543	1.1723	2.1266	.5485
119491**	.7321	.6931	1.4252	.6848
119490	.2136	1.6739	1.8875	.3662
119501**	0.0000	.0890	.0890	.0579
119500	0.0000	0.0000	0.0000	0.0000
120440	1.7073	3.8353	5.5426	1.2160
120450	1.5168	7.5375	9.0543	1.7347
120460	1.2525	1.7096	2.9621	.7349
120470	1.2842	5.3028	6.5870	1.3084
120480	.6216	.0899	.7115	.2695
120491*	2.4715	.1757	2.6472	.3473
120490*	1.0387	3.0597	4.0984	.3796
120500	0.0000	0.0000	0.0000	0.0000
121450	1.6005	5.4830	7.0835	1.4401
121460	1.3947	4.3686	5.7634	1.1988
121470	1.2118	3.3113	4.5231	.9731
121480	1.1397	2.0233	3.1630	.7459
121491	.9586	1.3341	2.2926	.5773
121490	.4982	2.0033	2.5015	.5264
121501	.0539	.2487	.3026	.0618
121500	.1144	0.0000	.1144	.0606
121510	0.0000	0.0000	0.0000	0.0000
122440	1.9253	4.2919	6.2171	1.3586
122450	1.6577	8.0434	9.7011	1.8600
122460	1.4852	2.3003	3.7856	.9042
122470	1.3711	5.9356	7.3067	1.4369

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
122480	.7238	.7684	1.4921	.4106
122491**	2.1713	1.9284	4.0997	1.9483
122490	.6983	4.5440	5.2423	.9950
122500	0.0000	0.0000	0.0000	0.0000
123450	1.8031	5.9612	7.7643	1.5811
123460	1.5468	4.8604	6.4072	1.3257
123470	1.3956	3.9929	5.3885	1.1408
123480	1.1821	2.7521	3.9342	.8760
123491	1.1841	1.8599	3.0440	.7366
123490	1.0429	1.8440	2.8869	.6865
123501	.0268	1.3191	1.3460	.2227
123500	.5395	0.0000	.5395	.2189
123510	0.0000	0.0000	0.0000	0.0000
124440	2.2917	4.4593	6.7510	1.5043
124450	1.9107	8.2860	10.1967	1.9807
124460	1.7286	2.7015	4.4301	1.0468
124470	1.5521	6.3551	7.9072	1.5623
124480	1.0658	1.1094	2.1752	.5798
124490	.9221	4.8474	5.7695	1.1188
124500	0.0000	0.0000	0.0000	0.0000
125460	1.7999	5.0924	6.8923	1.4448
125470	1.6172	4.4384	6.0556	1.2834
125480	1.3644	3.1662	4.5306	1.0013
125491**	1.5864	1.7642	3.3506	2.0222
125490	1.2343	2.4492	3.6835	.8462
125501*	.7980	.3459	1.1439	.1809
125500*	.8362	.3123	1.1485	.2168
125510*	.0869	.4521	.5390	.0610
125521*	0.0000	.1438	.1438	.0549
125520	0.0000	0.0000	0.0000	0.0000
126460	2.1210	2.8231	4.9440	1.1941
126470	1.8908	6.4153	8.3061	1.6830
126480	1.3583	1.3902	2.7485	.7208
126490	2.1152	3.3210	5.4363	1.2724
126500	.1219	.0386	.1605	.0592
126511	.7493	1.2888	2.0381	.5771
126510	.5842	2.1558	2.7400	.5743
126520	0.0000	0.0000	0.0000	0.0000
127470	1.9919	4.5848	6.5768	1.4291
127480	1.6383	3.3600	4.9983	1.1220
127491**	1.9573	2.2908	4.2481	2.7645
127490	1.5047	2.9066	4.4113	1.0076
127501*	1.1342	.4940	1.6282	.2576
127500*	.6746	1.4343	2.1089	.1770
127510*	.3181	.6443	.9624	.1976
127521	.0046	.0921	.0967	.1226
127520*	.2273	.0052	.2325	.0431
127530	0.0000	0.0000	0.0000	0.0000
128460	2.6985	2.6857	5.3842	1.3617
128470	2.6170	5.6715	8.2885	1.8052
128480	1.7219	1.5673	3.2892	.8681

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
128490	2.1523	4.2190	6.3713	1.4260
128500*	.2172	.5965	.8137	.0732
128511*	.9473	1.9861	2.9334	.2346
128510*	.4185	3.0961	3.5146	.1349
128520	0.0000	0.0000	0.0000	0.0000
129480	2.0760	3.2233	5.2993	1.2442
129490	1.9853	2.9871	4.9723	1.1784
129501**	1.2164	1.4708	2.6872	1.7728
129500	1.2183	1.0840	2.3023	.6252
129510*	.3591	1.3011	1.6602	.2166
129521*	.2140	.0298	.2438	.0690
129520*	.5339	.0729	.6068	.1292
129530**	.0624	.0400	.1024	.0460
129541	0.0000	.2361	.2361	0.0000
129540	0.0000	0.0000	0.0000	0.0000
130460	3.1294	4.5316	7.6610	1.7926
130470	4.5299	4.2233	8.7532	2.2142
130480	2.2306	1.5927	3.8233	1.0389
130490	3.0045	3.6260	6.6305	1.6140
130500	.5084	.6442	1.1526	.3134
130511*	1.0932	2.4895	3.5827	.2998
130510*	1.2607	2.1409	3.4016	.3274
130520	0.0000	0.0000	0.0000	0.0000
131480	3.0984	3.6849	6.7834	1.6532
131490	2.0478	3.7287	5.7765	1.3147
131500	1.2915	1.5401	2.8316	.7240
131510*	.7137	1.7025	2.4162	.2721
131521*	.1822	1.4911	1.6733	.1725
131520*	.6717	.4229	1.0946	.1838
131530*	.1855	.3893	.5748	.0793
131541*	0.0000	.1675	.1675	.0082
131540	0.0000	0.0000	0.0000	0.0000
132480	3.0362	2.6506	5.6867	1.4698
132490	4.3032	2.8789	7.1821	1.9290
132500*	.6603	1.3228	1.9831	.1315
132511*	1.6955	2.0386	3.7341	.3198
132510*	1.7221	2.0060	3.7281	.3905
132520*	.0601	.2686	.3287	.0169
132530*	.5247	2.2377	2.7624	.2375
132540	0.0000	0.0000	0.0000	0.0000
133490	3.5314	3.3417	6.8731	1.7456
133500	2.5208	1.5780	4.0987	1.1345
133510*	.5371	3.1625	3.6996	.3452
133521*	.5521	1.8662	2.4183	.2429
133520*	.8200	.9832	1.8032	.2443
133531	0.0000	1.6340	1.6340	0.0000
133530*	.4172	.5990	1.0162	.1338
133541*	0.0000	.2327	.2327	.0068
133540*	.1019	.0814	.1833	.0023
133550	0.0000	0.0000	0.0000	0.0000
134480	2.8079	3.9981	6.8080	1.6062

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
134490	3.9100	4.5553	8.4653	2.0622
134500	2.0354	1.4293	3.4647	.9512
134511*	2.9538	2.0944	5.0482	.4231
134510*	3.9516	0.0000	3.9516	.2764
134520*	.1521	.8250	.9771	.0478
134531*	0.0000	.3157	.3157	.0278
134530*	.6909	2.5927	3.2836	.2793
134541	0.0000	1.9654	1.9654	0.0000
134540	0.0000	0.0000	0.0000	0.0000
135500	2.3030	2.8749	5.1779	1.2661
135510	2.2364	2.4474	4.6837	1.1784
135520	1.7151	2.2196	3.9347	.9715
135530*	.3937	1.4560	1.8497	.2842
135541*	0.0000	.5268	.5268	.0036
135540*	.3099	.2614	.5713	.0053
135551	0.0000	1.6270	1.6270	0.0000
135550**	.0694	.0001	.0695	.0223
135561	0.0000	.2682	.2682	0.0000
135560	0.0000	0.0000	0.0000	0.0000
136480	3.3378	3.6436	6.9814	1.7253
136470	5.0252	3.2822	8.3074	2.2377
136500	2.1745	2.0170	4.1914	1.0891
136510	2.5643	3.7762	6.3405	1.4949
136520	1.4944	1.0873	2.5816	.7208
136531*	1.9390	1.9254	3.8644	.3489
136530*	1.8110	2.2135	4.0245	.4826
136540	0.0000	0.0000	0.0000	0.0000
137500	2.9863	2.5633	5.5495	1.4432
137510	2.1030	3.6081	5.7111	1.3163
137520	1.5770	2.7893	4.3663	1.0154
137530	1.8390	1.2575	3.0965	.8619
137540*	1.8407	.1953	2.0360	.1155
137550*	.1744	0.0000	.1744	.0017
137561*	0.0000	.6622	.6622	.0035
137560	0.0000	0.0000	0.0000	0.0000
138500	2.5788	1.9275	4.5063	1.2082
138510	3.3418	3.2608	6.6027	1.6720
138520	1.5806	1.6428	3.2234	.8368
138530	2.6414	2.3655	5.0069	1.3006
138540*	.6577	1.1951	1.8528	.1245
138551*	1.1469	2.0997	3.2466	.3484
138550*	1.2624	2.3291	3.5915	.2177
138560	0.0000	0.0000	0.0000	0.0000
139510	2.5357	3.4463	5.9821	1.4338
139520	2.1070	2.8034	4.9103	1.1925
139530	1.4153	3.3147	4.7300	1.0452
139540*	1.7868	.9275	2.7143	.1451
139550*	1.7637	.3108	2.0745	.1451
139560*	.8972	.0523	.9495	.1642
139570	0.0000	0.0000	0.0000	0.0000
140520	1.8762	1.7810	3.6572	.9559

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
140530	2.3044	3.6995	6.0039	1.3993
140540	1.2259	1.1062	2.3321	.6362
140550*	1.9312	2.1311	4.0623	.5320
140560*	.2803	.2169	.4972	.0419
140570*	.5170	2.2048	2.7218	.2733
140580	0.0000	0.0000	0.0000	0.0000
141530	1.8354	3.1791	5.0145	1.1627
141540	1.5084	2.4448	3.9532	.9402
141550	1.4982	1.4506	2.9488	.7804
141560*	.9155	.8879	1.8034	.1264
141570*	.9899	.0328	1.0227	.0655
141580*	.1595	.0717	.2312	.0371
141590	0.0000	0.0000	0.0000	0.0000
142520	1.8629	2.1486	4.0115	1.0091
142530	2.0611	5.0218	7.0829	1.5263
142540	1.4274	1.5165	2.9439	.7678
142550	1.8059	2.6856	4.4915	1.0765
142560*	.4283	1.0127	1.4410	.0992
142570*	.9470	2.5647	3.5117	.2024
142580	0.0000	0.0000	0.0000	0.0000
143540	1.4888	3.1351	4.6239	1.0421
143550	1.4553	2.2061	3.6615	.8854
143560	.9529	1.9242	2.8772	.6738
143570	.9294	.9940	1.9234	.5171
143580*	.4191	.2958	.7149	.1030
143590*	.3239	0.0000	.3239	.0612
143600	0.0000	0.0000	0.0000	0.0000
144540	1.3211	1.5114	2.8325	.7318
144550	1.7680	3.9910	5.7590	1.2693
144560	.8277	.7980	1.6258	.4544
144570	1.9032	1.0978	3.0010	.8619
144580*	.0830	.0289	.1119	.0031
144591*	.0003	.0597	.0600	.0091
144590*	1.2628	.0310	1.2938	.0055
144600	0.0000	0.0000	0.0000	0.0000
145540	1.4903	3.6217	5.1119	1.1188
145550	1.3811	2.8109	4.1920	.9559
145560	1.0440	2.5239	3.5680	.7992
145570	.9531	1.8262	2.7793	.6581
145580*	.6299	.7489	1.3788	.1903
145590*	.7047	.0138	.7185	.1360
145600	0.0000	0.0000	0.0000	0.0000
146540	1.5846	1.8539	3.4384	.8728
146550	2.3314	3.2382	5.5696	1.3382
146560	1.0753	1.2584	2.3337	.6111
146570	1.9653	1.7630	3.7283	.9872
146580*	.2427	.3143	.5570	.0864
146590*	.9279	1.6349	2.5628	.3325
146600	0.0000	0.0000	0.0000	0.0000
147560	1.0527	2.8453	3.8979	.8524
147570	.9642	2.2965	3.2607	.7365

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
147580	.6560	1.4800	2.1360	.5014
147590*	.7480	.8201	1.5681	.2411
147600*	.2417	.1187	.3604	.0873
147610*	.0630	.0001	.0631	.0106
147620	0.0000	0.0000	0.0000	0.0000
148540	1.8693	2.2529	4.1222	1.0295
148550	2.3816	3.8791	6.2607	1.4557
148560	1.0549	1.2715	2.3264	.6064
148570	1.1029	4.2278	5.3307	1.0859
148580	.4617	.5178	.9795	.2821
148590*	2.0435	.3000	2.3435	.2590
148600	0.0000	0.0000	0.0000	0.0000
149560	1.2106	3.2658	4.4764	.9715
149570	1.0244	2.8223	3.8467	.6399
149580	.7660	1.9302	2.6962	.6111
149590*	1.1578	.2513	1.4091	.2321
149600*	.4744	.3368	.8112	.0701
149610*	.3766	.0142	.3908	.0776
149620	0.0000	0.0000	0.0000	0.0000
150540	2.1520	2.5666	4.7186	1.1721
150550	2.5659	4.3736	6.9395	1.5952
150560	1.3051	1.7360	3.0410	.7631
150570	1.2062	4.7528	5.9590	1.2035
150580	.6298	.6898	1.3196	.3698
150590	1.7911	.8250	2.6161	.7835
150600	0.0000	0.0000	0.0000	0.0000
151570	1.2054	3.4327	4.6381	.9766
151580	.9005	2.4077	3.3082	.7334
151590	.5480	2.0083	2.5563	.5485
151600*	.6442	.8393	1.4835	.1856
151610*	.3119	.3096	.6215	.0938
151620	.0288	0.0000	.0288	.0119
151630	0.0000	0.0000	0.0000	0.0000
152560	1.5204	2.1988	3.7192	.9073
152570	1.3201	5.3981	6.7182	1.3429
152580	.9046	1.0699	1.9746	.5249
152590	.9498	3.7228	4.6726	.9559
152600	.3825	.0494	.4319	.1802
152611*	.4195	1.2873	1.7068	.2121
152610*	1.4388	.2881	1.7269	.2124
152620	0.0000	0.0000	0.0000	0.0000
153570	1.3744	3.9926	5.3671	1.1408
153580	1.0836	2.8996	3.9831	.8728
153590	.9109	2.4730	3.3839	.7475
153600	.5640	1.8689	2.4329	.5328
153610*	.6726	.0775	.7501	.0904
153620*	.2307	.1045	.3352	.0292
153630	0.0000	0.0000	0.0000	0.0000
154560	1.7579	2.7866	4.5445	1.0781
154570	1.5194	5.8649	7.3843	1.4824
154580	1.1308	1.5000	2.6307	.6691

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
154590	1.0421	4.4065	5.4486	1.0953
154600	.4301	.4889	.9190	.2664
154611**	1.0337	1.5223	2.5560	1.3203
154610	1.4592	.5239	1.9831	.6268
154620	0.0000	0.0000	0.0000	0.0000
155580	1.2530	3.4266	4.6796	1.0123
155590	1.0710	3.0435	4.1145	.8916
155600	.7684	1.9320	2.7004	.6143
155610	.7707	1.1309	1.9015	.4858
155620	.4917	.3221	.8138	.2553
155630	.0878	.0012	.0890	.0385
155640	0.0000	0.0000	0.0000	0.0000
156580	1.3605	2.0984	3.4588	.8399
156590	1.2393	4.8723	6.1116	1.2348
156600	.7044	.7766	1.4810	.4106
156610	.8969	3.0765	3.9734	.8368
156620	.2213	.0205	.2418	.1119
156630*	.4302	1.3177	1.7479	.2584
156640	0.0000	0.0000	0.0000	0.0000
157580	1.3921	3.9805	5.3726	1.1455
157590	1.2531	3.7420	4.9951	1.0624
157600	.9424	2.4379	3.3803	.7537
157610	.8010	1.9837	2.7847	.6331
157620	.5388	1.1405	1.6793	.4074
157630	.4881	.0567	.5449	.2131
157640	0.0000	0.0000	0.0000	0.0000
158580	1.5628	2.7384	4.3011	1.0076
158590	1.3843	5.4119	6.7962	1.3680
158600	.9557	1.2494	2.2380	.5829
158610	.9863	3.7539	4.7402	.9747
158620	.2445	.3421	.5866	.1708
158630	1.2455	.4286	1.6741	.5406
158640	0.0000	0.0000	0.0000	0.0000
159590	1.4124	4.4724	5.8848	1.2301
159600	1.0830	2.9830	4.0660	.8869
159610	.9741	2.6872	3.6613	.8039
159620	.6774	1.4851	2.1625	.5124
159630	.5954	1.0482	1.6436	.4121
159640	.3547	0.0000	.3548	.1527
159650	0.0000	0.0000	0.0000	0.0000
160580	1.7550	3.3115	5.0665	1.1611
160590	2.1367	4.9076	7.0443	1.5388
160600	1.2173	1.8152	3.0325	.7490
160610	1.1394	4.2807	5.4201	1.1094
160620	.5824	.6004	1.1827	.3400
160630	1.6093	.5874	2.1967	.6895
160640	0.0000	0.0000	0.0000	0.0000
161600	1.2192	3.7798	4.9990	1.0577
161610	1.1433	3.3891	4.5324	.9715
161620	.8118	2.0312	2.8429	.6456
161630	.6927	1.6492	2.3418	.5437

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
161640	.3250	1.0078	1.3329	.3070
161650	.1825	0.0000	.1825	.0925
161660	0.0000	0.0000	0.0000	0.0000
162600	1.4170	2.3779	3.7949	.9042
162610	2.1023	3.3114	5.4137	1.2787
162620	.8700	1.0223	1.8923	.5077
162630	.9216	3.0929	4.0145	.8493
162640	.3406	.4037	.7443	.2194
162651**	.6860	1.1460	1.8320	.9644
162650	.8650	.2331	1.0981	.3792
162660	0.0000	0.0000	0.0000	0.0000
163600	1.3863	4.3736	5.7599	1.2066
163610	1.3210	3.9876	5.3086	1.1251
163620	.9448	2.8141	3.7590	.8148
163630	.8897	2.2746	3.1643	.7114
163640	.3436	1.4370	1.7806	.3839
163650	.4855	.4010	.8866	.2664
163660	0.0000	0.0000	0.0000	0.0000
164600	1.6012	3.1559	4.7571	1.0875
164610	2.1371	4.1837	6.3208	1.4275
164620	1.1082	1.4820	2.5902	.6613
164630	1.9541	1.9560	3.9101	1.0186
164640	.3872	.4666	.8538	.2476
164650	1.4252	.4257	1.8509	.6049
164660	0.0000	0.0000	0.0000	0.0000
165610	1.4942	4.7885	6.2826	1.3084
165620	1.1208	3.3927	4.5135	.9653
165630	1.0734	2.8421	3.9156	.8634
165640	.6275	1.8641	2.4916	.5563
165650	.4918	1.5764	2.0682	.4623
165661	.0019	.1336	.1355	.2183
165660	.4547	.0578	.5125	.2014
165670	0.0000	0.0000	0.0000	0.0000
166620	1.3312	2.1714	3.5026	.8446
166630	2.0264	2.7799	4.8062	1.1721
166640	.6849	.7495	1.4344	.4012
166650	1.2757	1.8129	3.0885	.7710
166660	.0778	.2206	.2984	.0758
166671	.5272	.4519	.9791	.2914
166670	.6432	.1707	.8139	.2906
166680	0.0000	0.0000	0.0000	0.0000
167620	1.2973	4.0139	5.3112	1.1220
167630	1.2631	3.6023	4.8654	1.0468
167640	.8207	2.3700	3.1908	.7036
167650	.8915	1.6684	2.5599	.6174
167660	.2867	1.0390	1.3257	.2993
167670	.3442	.0184	.3626	.1520
167681	0.0000	.2078	.2078	0.0000
167680	0.0000	0.0000	0.0000	0.0000
168620	1.5334	2.9991	4.5325	1.0421
168630	1.9941	3.8149	5.8090	1.3241

NUCLIDE	E BETA	E GAMMA	E TOTAL	UNC TOTAL
168640	.9967	1.2267	2.2234	.5845
168650	1.4375	2.4176	3.8551	.9198
168660	.1881	.3215	.5096	.1442
168670	.9416	.3230	1.2646	.4262
168680	0.0000	0.0000	0.0000	0.0000
169630	1.4560	4.4495	5.9055	1.2442
169640	1.0157	2.9422	3.9579	.8603
169650	1.1169	2.3410	3.4579	.6007
169660	.5226	1.4087	1.9313	.4466
169670	.3339	1.1311	1.4650	.3328
169680	.1183	.0174	.1357	.0552
169690	0.0000	0.0000	0.0000	0.0000
170620	1.6775	3.6825	5.3600	1.1972
170630	1.9347	5.0888	7.0235	1.5043
170640	1.2624	1.8996	3.1620	.7804
170650	1.4591	3.3795	4.8385	1.0781
170660	.5454	.5952	1.1407	.3275
170671	.5495	2.4866	3.0361	.6268
170670	1.0852	1.2943	2.3795	.6268
170680	0.0000	0.0000	0.0000	0.0000
171640	1.2347	3.6087	4.8434	1.0389
171650	1.3196	3.1610	4.4806	.9982
171660	.6993	2.0055	2.7048	.6049
171670	.6969	1.4423	2.1392	.5155
171680	.3063	.6072	.9135	.2335
171690	.0362	0.0000	.0362	.0152
171700	0.0000	0.0000	0.0000	0.0000
172640	1.4311	2.5368	3.9679	.9371
172650	1.4589	4.5153	5.9742	1.2567
172660	.8899	1.0740	1.9639	.5249
172670	1.2744	1.9470	3.2214	.7929
172680	.1849	.2982	.4831	.1393
172690	.6228	.2294	.8522	.2930
172700	0.0000	0.0000	0.0000	0.0000

Appendix IV

COMPUTER PROGRAMS

WBGEA --- calculates the parameter "a" and departure energy for each nuclide.

WBGEB --- calculates the beta end-point energies for the possibe angular momentum states of the daughter (J_p, J_p+1, J_p-1), in turn, level densities at those end-point energies.

ABGE ---- calculates the average beta and gamma decay energies per disintegration from the fictitious level diagrams.

PROGRAM WBGEA

```
      PROGRAM WBGEA (INPUT,TAPE40,TAPE2,TAPE3,TAPE41,OUTPUT)
C     THIS PROGRAM WILL CALCULATE FOR EACH NUCLEUS THE PARAMETER
C     "A" AND THE DEPARTURE ENERGY AT LEVEL DENSITY VALUE OF
C     30 LEVELS/MEV.  TAPE 40 IS THE INPUT WHICH CONSISTS OF NAMES
C     OF NUCLEI (BY A SIX DIGIT NUMBER), BETA DECAY Q VALUES,
C     AND PARENT ANGULAR MOMENTA (J-2, -2 HAS NO PHYSICAL
C     MEANING, PURELY FOR PROGRAMING PURPOSE).  TAPE 2 AND
C     TAPE 3 ARE THE PAIRING ENERGIES AND SHELL CORRECTIONS
C     FOR          PROTON AND NEUTRON RESPECTIVELY.  TAPE 41
C     IS THE OUTPUT WHICH CONSISTS OF NAMES OF NUCLIDES, Q,
C     J-2, 30 LEVELS/MEV, PAIRING ENERGIES, EFFECTIVE ENERGIES
C     (U), DEPARTURE ENERGIES AND "A".
      DO 1 K=1,530
      READ(40,100) KA,KZ,K1,D2,Q,ZJ
  100 FORMAT(I3,I2,I1,A1,2X,F7.4,2X,F4.1)
      KN=KA-KZ-1
C     KN IS THE NEUTRON NUMBER OF DAUGHTER.
      DO 5 I=1,47
      READ(2,400) IZ,PZ,SZ
      IF(IZ.EQ.KZ+1) GO TO 6
C     KZ+1 IS THE CHARGE NUMBER OF DAUGHTER.
    5 CONTINUE
    6 PPZ=PZ
      SSZ=SZ
      REWIND2
      DO 7 J=1,73
      READ(3,500) IN,PN,SN
      IF(IN.EQ.KN) GO TO 8
    7 CONTINUE
    8 PPN=PN
      SSN=SN
      REWIND3
  400 FORMAT(I2,F4.2,F6.2)
  500 FORMAT(I3,F4.2,F5.2)
      A=FLOAT(KA)
      EE=PPZ+PPN
      S=SSZ+SSN
      AA=(0.00917*S+0.112)*A
      IF(KN.GE.86) AA=(0.00917*S+0.120)*A
      IF(KZ+1.GE.54) AA=(0.00917*S+0.120)*A
      DO 2 I=1,130000
      X=0.001*FLOAT(I-1)+0.1
C     X IS THE ENERGY INCREMENT IN ORDER TO GET DEPARTURE ENERGY.
      WX=(0.1477/((AA*(0.25)*(X**1.25)))*EXP(2.0*SQRT(AA*X))
C     WX IS THE TOTAL LEVEL DENSITY.
```

```
      IF(WX.GE.30.0) GO TO 3
      IF(X.GE.0) GO TO 1
  2   CONTINUE
  3   EEE=EE+X
C     EEE IS THE DEPARTURE ENERGY WHERE EE IS THE PAIRING
C     ENERGY AND X IS THE EFFECTIVE ENERGY AT 30 LEVELS/MEV.
      IF(EEE.GE.0) GO TO 1
      WRITE(41,200) KA,KZ,K1,D2,Q,ZJ,WX,EE,X,EEE,AA
  200 FORMAT(I3,I2,I1,A1,2X,F7.4,2(2X,F4.1),3(2X,F7.4),2X,F8.4)
  1   CONTINUE
      STOP
      END
```

PROGRAM WBGEB

```
      PROGRAM WBGEB (INPUT,TAPE41,TAPE42,OUTPUT)
C     THIS PROGRAM WILL CALCULATE FOR EACH NUCLEUS, BETA
C     END POINT ENERGY, LEVEL DENSITY (EQUATION 4.2) AT
C     THAT BETA END POINT ENERGY FOR EACH ANGULAR MOMENTUM
C     STATE OF DAUGHTER, NAMELY, J, J-1, J+1.
      COMMON ZJJ,Q,A,EE,AA
      DO 1 K=1,496
      READ(41,100) KA,KZ,K1,D2,Q,ZJ,EE,EEE,AA
  100 FORMAT(I3,I2,I1,A1,2X,F7.4,2X,F4.1,8X,F7.4,11X,F7.4,2X,F8.4)
      A=FLOAT(KA)
      ANSWER4=0.0
      ANSWER8=0.0
      DO 3 II=1,3
      J=0
      ZJ=ZJ+1.0
      ANSWER1=0.0
      ANSWER2=0.0
      ANSWER5=0.0
      IF(ZJ.LT.0.0) GO TO 3
      ZJJ=-ZJ*(ZJ+1.0)
      C=(0.5559/(A*AA))*(2.0*ZJ+1.0)
      DO 2 I=1,101
C     CALCULATION OF AVERAGE Q-E AS IN EQUATION (5.5), WHICH
C     IS ANSWER 3, FOR EACH J OF DAUGHTER.
      W=((Q-EEE)*2.0)/300.0
      IF(I.EQ.1) W=W/2.0
      IF(I.EQ.101) W=W/2.0
      J=J+1
      IF(J.EQ.2) W=2.0*W
      X=EEE+(FLOAT(I-1))*(Q-EEE)/100.0
      ANSWER1=ANSWER1+F(X)*W
      ANSWER2=ANSWER2+G(X)*W
      ANSWER5=ANSWER5+D(X)*W
      IF(J.EQ.2) J=0
    2 CONTINUE
      ANSWER6=C*ANSWER5
      ANSWER3=ANSWER1/ANSWER2
      Y=C*((EXP(2.0*SQRT(AA*(Q-EE-ANSWER3))+(5.6306*ZJJ)/(SQRT(
C     Y IS THE LEVEL DENSITY OF EQUATION (4.2) DIVIDED BY 2.
     $AA*(Q-EE-ANSWER3))*(A**0.6667))))/((Q-EE-ANSWER3)*(Q-EE
     $-ANSWER3)))
      ANSWER7=ANSWER6*ANSWER3
      WRITE(42,300) ZJ,Y,ANSWER3
  300 FORMAT(F4.1,2X,F7.1,2X,F7.4)
      ANSWER4=ANSWER4+ANSWER7
```

```
      ANSWER8=ANSWER8+ANSWER6
3     CONTINUE
      GAMMAE=Q-ANSWER4/ANSWER8
      WRITE(42,200) KA,KZ,K1,D2,Q,GAMMAE,EEE
200   FORMAT(I3,I2,I1,A1,2X,F7.4,2X,F7.4,2X,F7.4,/)
1     CONTINUE
      END
      FUNCTION F(X)
      COMMON ZJJ,Q,A,EE,AA
      F=(((Q-X)**6.0)/(0.0265*(AA*A)*((X-EE)**2.0)))*EXP(2.0*SQRT(AA
     $*(X-EE))+(5.6306*ZJJ)/(SQRT(AA*(X-EE))*(A**0.6667)))
      RETURN
      END
      FUNCTION G(X)
      COMMON ZJJ,Q,A,EE,AA
      G=(((Q-X)**5.0)/(0.0265*(AA*A)*((X-EE)**2.0)))*EXP(2.0*SQRT(AA
     $*(X-EE))+(5.6306*ZJJ)/(SQRT(AA*(X-EE))*(A**0.6667)))
      RETURN
      END
      FUNCTION D(X)
      COMMON ZJJ,Q,A,EE,AA
      D=(EXP(2.0*SQRT(AA*(X-EE))+(5.6306*ZJJ)/(SQRT(AA*(X-EE))
     $*(A**0.6667))))/((X-EE)*(X-EE))
      RETURN
      END
```

PROGRAM ABGE

```
      PROGRAM ABGE (INPUT,TAPE1,TAPE43,TAPE5,TAPE44,OUTPUT)
C     THIS PROGRAM WILL CALCULATE FOR EACH NUCLEUS, ITS
C     AVERAGE BETA AND GAMMA DECAY ENERGIES FROM FICTITIOUS
C     LEVEL DIAGRAM.  TAPE 1 IS THE CONSTANTS OF EQUATION
C     (5.9) AND TAPE 2 IS THE CONSTANTS OF HINDRANCE
C     FACTOR*100.
      COMMON D0,D1,D2,W0
      DIMENSION AEBETA0(15),ZLAMDA0(15),ZLAMDA1(15),AEBETA1(15),
     $AEGAM0(15),AEGAM1(15)
C     AEBETA, AEGAM, AND ZLAMDA ARE THE LEVEL BETA, GAMMA
C     ENERGY AND ITS PROBABILITY.  0 FOR ALLOWED TRANSITION
C     (I.E. AEBETA0), 1 FOR FIRST FORBIDDEN TRANSITION.
      ZME=0.5110034
      DO 14 LL=1,520
      READ(43,300) KA,KZ,K1,D2,Q,N0,N1
C     N0 IS THE NUMBER OF LEVELS WHICH HAVE ALLOWED TRANSITIONS
C     AND N1 IS THE NUMBER OF LEVELS WHICH HAVE FIRST FORBIDDEN
C     TRANSITIONS.
  300 FORMAT(I3,I2,I1,A1,F7.4,I3,I1)
      ZLAMDA=0.0
      AEB0=0.0
      AEG0=0.0
      AEB1=0.0
      AEG1=0.0
      DO 1 I=1,47
      READ(1,200) IZ,A0,A1,A2
  200 FORMAT(2X,I2,3(2X,E10.4))
      IF(IZ.EQ.KZ) GO TO 2
  1   CONTINUE
  2   B0=A0
      B1=A1
      B2=A2
      REWIND 1
      DO 3 J=1,47
      READ(5,400) JZ,C0,C1,C2
  400 FORMAT(I2,3(E11.4))
      IF(JZ.EQ.KZ) GO TO 4
  3   CONTINUE
  4   D0=C0
      D1=C1
      D2=C2
      REWIND 5
      IF(N0.EQ.0) GO TO 15
      ZLAOT=0.0
      DO 5 K=1,N0
```

```
C     CALCULATION OF AVERAGE BETA DECAY ENERGIES BY USING
C     THE THEORY OF V.8 FOR ALLOWED TRANSITION.
      AEBETA0(K)=0.0
      READ(43,500) ZLDEN,EBETA
  500 FORMAT(F8.1,F7.4)
      ZLAMDA0(K)=(EBETA**5.0)*ZLDEN
      AEBON=0.0
      AEBOD=0.0
      M=0
      AEGAM0(K)=Q-EBETA
      W0=EBETA/ZME
      DO 6 L=1,101
      W=(W0*2.0)/300.0
      IF(L.EQ.1) W=W/2.0
      IF(L.EQ.101) W=W/2.0
      M=M+1
      IF(M.EQ.2) W=2.0*W
      X=(FLOAT(L-1)*W0)/100.0
      AEBON=AEBON+F(X)*W
      AEBOD=AEBOD+G(X)*W
      IF(M.EQ.2) M=0
  6   CONTINUE
      AEBETA0(K)=AEBETA0(K)+AEBON/AEBOD
      ZLAOT=ZLAOT+ZLAMDA0(K)
  5   CONTINUE
      GO TO 17
  15  ZLAOT=0.0
      DO 16 MM=1,NO
      AEBETA0(MM)=0.0
      AEGAM0(MM)=0.0
  16  CONTINUE
  17  IF(N1.EQ.0) GO TO 8
      ZLA1T=0.0
      DO 7 N=1,N1
C     CALCULATION OF AVERAGE BETA DECAY ENERGIES BY USING
C     THE THEORY OF V.8 FOR FIRST FORBIDDEN TRANSITION.
      AEBETA1(N)=0.0
      READ(43,500) ZLDEN,EBETA
      S=0.01*(B0+B1*EBETA+B2*EBETA*EBETA)
      IF(N0.EQ.0) S=1.0
      ZLAMDA1(N)=(EBETA**5.0)*ZLDEN*S
      AEB1N=0.0
      AEB1D=0.0
      M=0
      AEGAM1(N)=Q-EBETA
```

```
      W0=EBETA/ZME
      DO 9 II=1,101
      W=(W0+2.0)/300.0
      IF(II.EQ.1) W=W/2.0
      IF(II.EQ.101) W=W/2.0
      M=M+1
      IF(M.EQ.2) W=2.0*W
      X=(FLOAT(II-1)*W0)/100.0
      AEB1N=AEB1N+FF(X)*W
      AEB1D=AEB1D+GG(X)*W
      IF(M.EQ.2) M=0
    9 CONTINUE
      AEBETA1(N)=AEBETA1(N)*AEB1N/AEB1D
      ZLA1T=ZLA1T+ZLAMDA1(N)
    7 CONTINUE
      GO TO 11
    8 ZLA1T=0.0
      DO 10 JJ=1,N1
      AEBETA1(JJ)=0.0
      AEGAM1(JJ)=0.0
   10 CONTINUE
   11 ZLAT=ZLA0T+ZLA1T
C     ZLAT IS THE SUM OF PROBABILITY (NOT NORMALIZED).
      DO 12 KK=1,N0
C     NORMALIZATION OF PROBABILITY FOR ALLOWED TRANSITIONS.
      ZLAMDA0(KK)=ZLAMDA0(KK)/ZLAT
      AEBETA0(KK)=AEBETA0(KK)*ZLAMDA0(KK)
      AEGAM0(KK)=AEGAM0(KK)*ZLAMDA0(KK)
      AEG0=AEG0+AEGAM0(KK)
      AEB0=AEB0+AEBETA0(KK)
   12 CONTINUE
      DO 13 NN=1,N1
C     NORMALIZATION OF PROBABILITY FOR FIRST FORBIDDEN TRANSITIONS.
      ZLAMDA1(NN)=ZLAMDA1(NN)/ZLAT
      AEGAM1(NN)=AEGAM1(NN)*ZLAMDA1(NN)
      AEBETA1(NN)=AEBETA1(NN)*ZLAMDA1(NN)
      AEB1=AEB1+AEBETA1(NN)
      AEG1=AEG1+AEGAM1(NN)
   13 CONTINUE
      AVEBETA=(AEB0+AEB1)*ZME
      AVEGAM=AEG0+AEG1
      TOTAL=AVEBETA+AVEGAM
C     AVEBETA AND AVEGAM ARE THE AVERAGE BETA AND GAMMA DECAY
C     ENERGIES PER DISINTEGRATION AND TOTAL IS THEIR SUM.
      SIGMAB=0.0701*Q
```

```
      SIGMAG=0.1402*Q
      SIGMAT=0.1567*Q
      WRITE(44,600) KA,KZ,K1,D2,AVEGETA,SIGMAB,AVEGAM,SIGMAG,
     $TOTAL,SIGMAT
600   FORMAT(2X,I3,I2,I1,A1,1X,6(2X,F7.4))
14    CONTINUE
      STOP
      END
      FUNCTION F(X)
      COMMON D0,D1,D2,W0
      F=X*(D0+D1*(X+1.0)+D2*(X+1.0)*(X+1.0))*(X+1.0)*(W0-X)*(W0-X)
      RETURN
      END
      FUNCTION G(X)
      COMMON D0,D1,D2,W0
      G=(D0+D1*(X+1.0)+D2*(X+1.0)*(X+1.0))*(X+1.0)*(W0-X)*(W0-X)
      RETURN
      END
      FUNCTION FF(X)
      COMMON D0,D1,D2,W0
      FF=X*(D0+D1*(X+1.0)+D2*(X+1.0)*(X+1.0))*(X+1.0)*(W0-X)*(W0-X)
     $*(((X+1.0)*(X+1.0)-1.0)*(W0-X)*(W0-X))
      RETURN
      END
      FUNCTION GG(X)
      COMMON D0,D1,D2,W0
      GG=(D0+D1*(X+1.0)+D2*(X+1.0)*(X+1.0))*(X+1.0)*(W0-X)*(W0-X)
     $*(((X+1.0)*(X+1.0)-1.0)*(W0-X)*(W0-X))
      RETURN
      END
```