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MICROSCOPIC BETA AND GAMMA DATA FOR DECAY-HEAT NEEDS

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MICROSCOPIC BETA AND GAMMA DATA FOR DECAY-HEAT NEEDS

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ABSTRACT

Microscopic beta and gamma data for decay-heat needs are defined as absolute-intensity spectral distributions of beta and gamma rays following radioactive decay of radionuclides created by, or following, the fission process. Four well-known evaluated data files, namely the U.S. ENDF/B-V, the U.K. UKFPDD-2, the French BDN (for fission products), and the Japanese JNDC Nuclear Data Library, are reviewed. Comments regarding the analyses of experimental data (particularly gamma-ray data) are given; the need for complete beta-ray spectral measurements is emphasized. Suggestions on goals for near-term future experimental measurements are presented.

INTRODUCTION

"Heat" is a form of energy. However, "decay heat" is usually considered as a form of power, or heat rate. Generally, the term "decay heat" refers to the rate of generation of energy due to the decay of radionuclides created during power production in a fission reactor. In this report, decay of fission-product ($72 \leqslant A \leqslant 167$) radionuclides will be considered; heavy actinides that are produced during power production also contribute to "decay heat" but will not be discussed further.

Fission-product decay heat has been measured [1-6] for a variety of (a) fuel-element isotopes, (b) irradiation histories, and (c) cooling and counting time histories. If one defines [7] a function f(t,T) as the instantaneous fission-product decay heat (power) $\underline{t}$ seconds following an irradiation period of $\underline{T}$ seconds, the dependence of f(t,T) ~~as a function of~~ on $\underline{t}$ is roughly t^{-1}. Hence, it is common practice to exhibit decay heat as

$$t \times f(t,T) \quad \text{vs} \quad t \, .$$

Results of one set of experiments [1] are shown in Fig. 1 for the decay heat of radionuclides produced by very nearly instantaneous irradiations ($\underline{T}$ short compared with $\underline{t}$) of standard thermal-reactor fuel isotopes ^{235}U, ^{239}Pu, and ^{241}Pu. [In this figure $f(t,0) \equiv f(t)$.]

There are many measurement techniques used in decay-heat measurements. The ORNL [1] results shown in Fig. 1 were deduced from spectral measurements. An example of a beta-ray "energy" spectrum [8] obtained for ^{241}Pu decay heat is shown in Fig. 2. In this figure, the ordinate is shown as $E_\beta \times N(E_\beta)$, and so is not a particle spectrum but an energy spectrum. To obtain the beta-ray decay energy released for the irradiation, cooling and counting times given in the legend requires only the determination of the "area" bounded by the data and the axis of abscissas, i.e.,

$$< E_\beta >_D = \int E_\beta \, N(E_\beta) dE_\beta \quad . \tag{1}$$

Similar data were obtained [1,8] for spectral distribution of gamma rays (using a NaI detector), and similar manipulations of the data yielded the gamma-ray decay energy release, $< E_\gamma >_D$. The total decay energy release is just the sum of $< E_\beta >_D$ plus $< E_\gamma >_D$.

$$E_D = < E_\beta >_D + < E_\gamma >_D \quad . \tag{2}$$

The decay heat is approximately determined as E_D/T_{count}.

What are decay heat "Needs"? To begin with, let us temporarily substitute the word "Calculations" for "Needs". This substitution leads to "theory-compared-with-experiment" graphics. For decay heat the accepted calculational technique involves computing the yield of each and every radionuclide at some time $\underline{t}$ seconds following a specified fission irradiation period. The total decay energy, $(E_D)_i$, of a given fission product is weighted by the yield of that fission product, $Y_i(t,T)$; all of these weighted decay energies are added together. That is, total decay energy is simply

$$\sum_i (E_D)_i \, Y_i(t,T) \quad . \tag{3}$$

There are quite a few computer codes [9-13] written to determine the $Y_i(t,T)$; these will not be discussed in this report. The "Needs," then, are the nuclear data required for the calculations, i.e., fission-product yields and decay heats. Radionuclide half-lives are needed, as are neutron interaction cross sections; these needs are not discussed in the present review. The fission-product yields are treated thoroughly in other reviews [14-17]. We consider herein only the beta and photon decay energies and how to fulfill the "Needs" for these data.

It must be apparent that the input data must consist of very many separate values of $(E_D)_i$, one for each radionuclide produced either directly during the fission process or else subsequently (indirectly) as the result of the decay of directly- or other indirectly-produced radionuclides. There are essentially no modern experiments that yield a total E_D (nor $< E_\gamma >_D$ nor $< E_\beta >_D$) for any specific radionuclide. Rather, most modern experiments are measurements of gamma-ray spectra using high-resolution detectors. From these data a level structure of the daughter is deduced, and to provide intensity balances, characteristics of the beta-ray decay of the parent are deduced. Such deductions are occasionally, but not as a rule, augmented by direct beta-ray decay measurements. As an example, the decay of a well-known fission product, ^{137}Cs, is exhibited in Fig. 3.

Now, "Microscopic Beta and Gamma Data" (or MBG) can be defined. First observe that insofar as decay-heat calculations are concerned, the "Beta and Gamma" data that are *needed* are just the integral quantities $< E_\beta >_D$, as defined by Eq. (1), and $< E_\gamma >_D$, their equivalents for fission-product gamma radiation. However, as pointed out above, these quantities are rarely directly measured in modern experiments; instead spectral measurements are made, and these are analyzed to deduce level-structure information. Very often, then, one must *start* with the deduced or evaluated level-structure information to determine the desired integral quantities. So, finally, "Microscopic" may be defined as the $N(E_x)$, where *x* is β and γ, for the MBG portion of the title.

In summary, then:

Microscopic Beta and Gamma Data for Decay Heat Needs are *Absolute Intensity Spectral Distributions of Beta and Gamma Rays Following Radioactive Decay of Each Radionuclide Created Directly or Indirectly During Fission.*

EXAMPLE: DATA FOR DECAY OF ^{137}Cs AND ^{137}Ba*

It seems necessary to provide a certain precision to the definition of the title of this report, because almost always the reported evaluated decay information do not directly contain all of the "data needs." They often do not include all of the necessary information *to deduce* what is required for the calculations. Such a situation, for example, is illustrated by the information for ^{137}Cs decay shown in Fig. 3.

This figure exhibits the decay of *two* fission products: (1) the beta decay of ^{137}Cs, and (2) the internal-transition decay of the 2.55-min isomer of ^{137}Ba. Let us investigate the latter decay first. The MBG data given directly are (a) the gamma-ray energy $E^0_\gamma = 661.4$ keV, and (b) the fraction of the decay, 89.9%, that this gamma-ray represents. We can classify these two data as "direct" because the function $N(E_\gamma)$ is essentially a delta function, $\delta(E_\gamma - E^0_\gamma)$, having an area equal to 0.899/decay. There is no direct representation of the other 10.1% of the decay of this isomer. Let us see how much of the other 10.1% can be deduced from information given in Fig. 3. Three data exhibited in this figure will provide some assistance: (a) the transition energy (661.4 keV), (b) the multipolarity (M4), and (c) the Z (56) of the Ba nucleus. From these data the total conversion-electron production can be deduced, using published tables, [18] that is, using information not given in Fig. 3. The characterization of this decay is not complete, however, for one must now determine the atomic decay of the disturbed electronic configuration. These can be accomplished using tabulated fluorescent yields [19]. Such information is not given in Fig. 3. However, by using additional information as needed, one can complete the characterization of the decay of ^{137}Ba* so as to provide a complete $N(E_\gamma)$ data set including x-ray contributions, and a complete $N(E_e) \equiv N(E_\beta)$ data set including conversion-electron contributions.

Turning now to the beta decay of ^{137}Cs, as represented in Fig. 3, there are only two MBG data: the two values of I_β, one for each of the two transitions. From the definition above, the other MBG data for ^{137}Cs beta decay are relative intensity $N(E_\beta)$ for $0 \leq E_\beta \leq$ 512 keV, and for $0 \leq E_\beta \leq$ 1173 keV, respectively, for the two beta-ray transitions shown in Fig. 3. Neither of the two given values of $E_{\beta max}$ nor the two given log(ft) values nor the total energy Q_β is "direct" MBG data. One may observe that the $N(E_\beta)$ vs E_β of the dominant $E_{\beta max}$ = 512 keV can be computed from beta-decay theory because it is a first-forbidden-unique transition. ($E_{\beta max}$ = 512 keV is an indirect MBG datum.) However, the $N(E_\beta)$ vs E_β of the second-forbidden-nonunique 1173-keV transition cannot be computed. They must be measured to obtain correct MBG data.

Thus, even in these simple, well-known decay schemes, we find that effort must be expended by the data-file evaluator to obtain the MBG data. More complex decay schemes lead to an increased probability of less-than-perfect data evaluations, particularly for $N(E_\beta)$. Measurements for applied purposes are needed.

EVALUATED DATA FILES

To perform summation decay heat calculations requires $< E_\beta >_D$ and $< E_\gamma >_D$ for each and every fission product; and to perform calculations for comparisons with "spectral" data such as exhibited in Fig. 2 requires spectral information, $N(E_\beta)$ vs E_β, for each and every transition due to decay of each and every fission product. The existing experimental data have been thoroughly examined and evaluated, and evaluated results have been collected in a systematic manner in compilations known as data files. These files are prepared in standardized computer formats so that the desired information can be readily extracted as needed. They contain values for the desired integral quantities and may also contain differential or spectral data.

Four of the most used of these data files will be reviewed in this section. These four files are: (1) U.S. ENDF/B-V Fission-Product Data Files [20]; (2) U.K. UKFPDD-2 Revised Fission Product Decay Data File [21]; (3) French Library of Nuclear Data for Fission Products [22]; and (4) Japanese Nuclear Data Committee JNDC Nuclear Data Library of Fission Products [23]. Table 1 gives an overview of the extent of each of these files.

Evaluations of each of these files starts with study of those experimental results that are deemed to be complete, e.g., for the fission-product decay schemes such as shown in Fig. 3. Even in these easy cases, however, the evaluator must provide additional information to obtain a complete MBG data set. For example, the ENDF/B-V evaluation provides a total (integral) electron energy which for some radionuclides includes specific contributions from the conversion electrons and Auger electrons as well as the beta decay electrons; and similarly the total photon energy may include specific contributions from X radiation as well as gamma radiation. The JNDC evaluation, on the other hand, provides a total energy associated with internal conversion; the division between photon and electron energy is not specified.

Although there is some utilization of the evaluated data of one or several files by the evaluators of another file, the four files are primarily the results of four independent evaluations. Differences in evaluations for "well-known" decay tend to be minor. Table 2 exhibits $< E_\beta >_D$ and $< E_\gamma >_D$ taken from the four files for 10 long-lived fission products and 4 short-lived daughter fission products. (In this table, $< E_\beta >_D \equiv E_\beta$ and $< E_\gamma >_D \equiv E_\gamma$.) The overall agreement is very good; indeed, one might expect "perfect" agreement except for differences in round-off values. There are a few values of E_β in this table, in particular (a) ^{90}Sr JNDC, (b) ^{103}Ru FLNDFP, (c) ^{125}Sb UKFPDD-2, and (d) ^{137}Ba* FLNDFP, which are at a substantial variance from the other similar E_β for the given radionuclide. For some E_β values, differences could be due (perhaps) to the choice of the $N(E_\beta)$ vs E_β electron-distribution function for a given transition. A comparison of two different computed electron distributions compared with some experimental data [24] is shown in Fig. 4.

Comparisons similar to those in Table 2 but now for shorter-lived fission products are exhibited for 14 radionuclides in Table 3. These radionuclides were selected from among those fission products having relatively large yields in fission. Basically, what is observed is that for well-known (or at least agreed upon) decay nuclear data the integral energies are in agreement. There are evidences of individual evaluation, however, for example, for ^{86}Br, ^{94}Y, and ^{140}Cs. For the two ^{136}I isotopes, the evaluations are in disagreement — very likely because of different experimental data available to each evaluator at the time of evaluation.

Indeed, a scan of each of these tables vis-a-vis each other does show a rather substantial independence, although there are definite acknowledgments of mutual "borrowing" of evaluated data. Differences in evaluated $< E_\gamma >_D$ are likely due to choices involving evaluation of experimental results.

The evaluator has a basic decision to make at the initiation of study of the decay characteristics of a given radionuclide. Does one adopt the results of one particular experiment (in effect evaluating experimental procedures) or does one take averages of several sets of results (in effect accepting more than one set of experimental procedures as equally valid). Such choices have to be made for evaluating the decay data of every fission product. One would prefer the first choice, since then one may expect the reported results at least to be consistent. One should be concerned, however, to evaluate critically all experiments, and not accept any data set just because it is the only reported data set for decay of a given radionuclide.

ASSESSMENT OF EXISTING BETA AND GAMMA DATA

With the creation of on-line isotope "separators" over the past decade, many new measurements have been performed and reported concerning the decay of short-lived fission products. The experiments can be divided (roughly) into two types: (a) β-γ coincidence measurements used principally to determine Q_β, and (b) high-resolution gamma-ray spectral measurements to deduce level structure information. (Delayed-neutron measurements are discussed in detail in other review papers [25,26]. Radionuclide lifetimes are usually determined but are not often the primary goal of a given experiment.) What conclusions can be deduced concerning the generation of MBG data for decay-heat needs from the recent, as well as the past, measurements? I suggest several apply generally, although not necessarily to a specific experiment.

1. The high-resolution gamma-ray measurements directly produce E_γ and I_γ, i.e., MBG data. By their very nature, however, these experiments, can,

and very often do, fail to provide a complete data set of (E_γ, I_γ) pairs. One must ask how important is the "missing" information for decay heat needs?

2. Very few MBG N(E_β) data exist in the literature. However, in a rather recent report [27] Aleklett and Rudstam have reported $< E_\beta >_D$ for fission products without reporting beta-ray spectra. In this case, the specific data for decay heat needs have been reported, but MBG data were not. Recently, Rudstam [28] has initiated a program to provide MBG N(E_β) data for individual fission products.

3. Such beta-ray data as are in the literature, namely end-point (or transition) energies, $E_{\beta max}$, and transition intensities, I_β, have been deduced, for most cases, following level structure evaluation of measured (E_γ,I_γ) in gamma-ray high-resolution experiments. Until recently, "complete" beta-ray spectral measurements existed only for relatively long-lived radionuclides [29]. (Even the more complete beta-ray spectral measurements often do not report the low-energy portion of the spectrum.)

4. Even for those radionuclides for which the high-resolution gamma-ray data are essentially complete and for which the evaluation of these data result in a substantially correct level structure of the daughter nucleus so that the deduced $E_{\beta max}$ and I_β for the beta-ray transitions are also substantially correct, one still does not necessarily have the required information to compute N(E_β) vs E_β. One must postulate the character of each transition; then having done so one may be able to compute the spectrum of beta rays for each transition in the decay and then sum these spectra. One can compute beta-ray spectral distributions for individual allowed and for forbidden unique transitions. However, more information is needed for forbidden non-unique transitions, information simply not available from the analysis of high resolution gamma-ray measurements. Lacking any additional guidance for a given forbidden transition, the allowed spectral distribution is usually postulated. (Recall the comparison of two different computed shapes for decay of ^{90}Y shown in Fig. 4.)

5. "Systematics" are often invoked to provide guidelines for level-structure evaluation of experimental high-resolution gamma-ray data. When systematics are based on basic physical principles (e.g., angular correlation interpretations) the resulting conclusions may be accepted with some confidence. However, evaluated results based on systematics strongly dependent upon nuclear model expectations are not as reliable, although the rule that $J^\pi = 0^+$ for ground states of even-even nuclides has yet to be violated.

Systematics of beta decay are very ill-defined. Figure 5 exhibits a compilation of log(ft) values for prominent ($I_\beta > 50\%$) transitions observed in fission product decay. Even for these strong transitions, there is a substantial spread in log(ft) values for the three types of transitions. Even the recommended [30] guidelines (shown in the figure at 5.9 for first-forbidden non-unique and at 8.5 for first-forbidden unique) used in evaluations in the U.S. are ad hoc, and there is certainly no guarantee that they remain valid for radionuclide decay characterized, in part, by a large Q_β.

Systematics for level-to-level decay in the same nucleus must also be treated with some care. For example, determination of a possible transition multipolarity based upon a measured lifetime may have much leeway and little reliability. Measurements of intensities of conversion electrons, especially with a measurement of the photon intensity, provides much more reliable data for multipolarity determinations. Measurements of angular correlations of sequential transitions tend to be very tedious and the results have large uncertainties. Such measurements, however, yield information on spin sequences, usually in conjunction with other helping data.

6. There is no theory to accurately compute MBG data from "basic" principles. One must, perforce, have measured data. Measured data, however, are not yet available for all fission products.

CONCLUSIONS AND RECOMMENDATIONS

For existing "complete" MBG data for radionuclide~~s~~ decay characterized by $Q_\beta < 5$ MeV, the four compilations are in substantial agreement. There are differences of varying degrees noted for decay of specific radionuclides, but these differences are unlikely to affect decay heat calculations very much. For radionuclide decay characterized by $Q_\beta > 5$ MeV, the JNDC compilation [23] determines $< E_\beta >_D$ using the "gross theory of beta decay." [31] whereas the other evaluations rely on MBG data. These different $< E_\beta >$ do provide differing decay-heat results. The major differences in overall decay-heat calculations using the different files can be ascribed to the different manners with which the different evaluations have determined integral energies $< E_\beta >_D$ and $< E_\gamma >_D$ for those radionuclides lacking complete or even incomplete MBG data.

This aspect is not treated in this review. Whatever technique is used to determine integral energies for such radionuclides, the values, and uncertainties assigned to these values, have little reliability. They will be used for decay heat calculations only until experimental MBG data become available.

New data are becoming available! However, by the very nature of the evaluation process, there is a lag time between data availability and its inclusion in evaluated files. Although decay heat analyses would definitely benefit from a reduction of this lag time, said reduction should not be effected at the expense of quality of evaluation. Indeed, the present high quality must be maintained. The experimenters can be of substantial assistance by recognizing the utility in presenting their results in a manner to assist the evaluators. Right now, most of the experiments have some detailed level structure as the final goal, a goal which will surely (in the future) lead to a better understanding of the basic nuclear physics theory. So this goal should be maintained. However, in the process of studying and presenting the results of their experiments, it would be an additional benefit if such reports considered MBG data needs. For example, estimates of the integral quantities $< E_\beta >_D$ and $< E_\gamma >_D$ will not only be directly useful for decay heat needs, but by requiring the total "measured" energy of the decay (including neutrino energy) to equal Q_β, will likely assist in obtaining a more reliable evaluation of the daughter level structure.

For decay heat purposes, some previously studied radionuclides need to be reexamined. For example, Aleklett and Rudstam [27] include in their report a graphic of the important radionuclides for beta-ray decay heat. These include six yttrium isotopes, namely, ^{90}Y, ^{91}Y, ^{92}Y, ^{93}Y, ^{94}Y, and ^{95}Y, as being among the most important of the important radionuclides.

Present information on ^{95}Y rests upon the results of a single experiment,[32] and there are only two experiments [33,34] reporting data for ^{94}Y. One may, indeed, recommend reexamination of the decay of these isotopes as well as decay of other radionuclides important for decay-heat needs.

In summary, the burden of improving the status of MBG data for more reliable decay heat calculations is now in the hands of the experimentalists. New experimental equipment has opened up new regions of the periodic table for study. High-resolution gamma-ray measurements by themselves yield a great deal of information for both level-structure and decay-heat needs. More attention ought to be given to beta-ray measurements, not only end-point measurements but also total beta-ray spectral measurements. In addition, the need for reliable uncertainties on intensities has not been emphasized; uncertainties, however, are required to ascertain degrees of validity of the calculated decay-heat functions, f(t,T).

We are in a science that demands careful work and attention to detail. Developing a decay scheme and a level structure requires analyses of many pieces of information, much like a jigsaw puzzle. Developing an understanding of nuclear behavior requires study of many decay schemes. The timely realization of that goal is still beyond prediction; however, the near-term realization of the goal of satisfying the MBG data needs is well within reach if research groups will include this goal as part of the overall justification for their efforts.

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Table 1. Summary of four fission-product data files

	ENDF/B-V (ref. 20)	UKFPDD-2 (ref. 21)	FLNDFP (ref. 22)	JNDC (ref. 23)
Radioactive nuclides	750	736	558	1020
Nuclides with spectra	264	390	458[a]	n.a.[b]
Nuclides with theoretical decay energies	333	346	152	469
Nuclides with theoretical half lives	192	197	59	283

[a] Including I_γ (relative) information.

[b] Not available.

Table 2. Total beta-ray and gamma-ray energies (in MeV) for long-lived radionuclides

Radio-nuclide	$T_{1/2}$	ENDF/B-V		UKFPDD-2		FLNDFP		JNDC	
		E_β	E_γ	E_β	E_γ	E_β	E_γ	E_β	E_γ
^{89}Sr	50 d	0.583		0.583		0.583		0.568	
^{90}Sr	29 y	0.196		0.196		0.196		0.174	
^{90}Y	64 h[a]	0.937		0.934		0.935		0.933	
^{95}Zr	64 d	0.118	0.733	0.118	0.735	0.116	0.737	0.117	0.733
^{103}Ru	39 d	0.075	0.469	0.070	0.484	0.107	0.489	0.072	0.470
^{106}Ru	368 d	0.010		0.010		0.010		0.010	
^{106}Rh	30 s[a]	1.414	0.205	1.421	0.210	1.412	0.209	1.421	0.197
^{125}Sb	3 y	0.096	0.435	0.112	0.427	0.097	0.431	0.087	0.439
^{137}Cs	30 y	0.187		0.187		0.174		0.171	
^{137}Ba*	3 m[a]	0.064	0.598	0.064	0.597	0.018	0.597	0.068	0.594
^{144}Ce	284 d	0.091	0.020	0.091	0.020	0.091	0.021	0.091	0.020
^{144}Pr	17 m[a]	1.209	0.029	1.213	0.033	1.209	0.029	1.214	0.030
^{147}Nd	11 d	0.266	0.136	0.271	0.140	0.269	0.140	0.272	0.145
^{154}Eu	8 y	0.282	1.226	0.278	1.230	0.278	1.254	0.281	1.215

[a] "Effective" $T_{1/2}$ is that of the parent given one row above.

Table 3. Total beta-ray and gamma-ray energies (in MeV) for some important short-lived radionuclides

Radionuclide	$T_{1/2}$	ENDF/B-V		UKFPDD-2		FLNDFP		JNDC		$\sigma/\bar{E}_\gamma$ (%)
		E_β	E_γ	E_β	E_γ	E_β	E_γ	E_β	E_γ	
^{84}Br	32 m	1.249	1.754	1.256	1.753	1.269	1.738	1.254	1.788	1.2
^{86}Br	55 s	1.780	3.300	1.775	3.318	1.932	3.252	1.847	2.936	5.6
^{89}Kr	3 m	1.346	1.870	1.350	1.785	1.374	1.825	1.328	1.844	2.0
^{93}Sr	7 m	0.697	1.930	0.665	1.939	0.693	2.214	0.688	1.978	6.7
^{94}Y	19 m	1.798	0.772	1.789	0.771	1.700	1.111	1.813	0.772	19.8
^{101}Mo	15 m	0.585	1.386	0.506	1.502	0.525	1.514	0.511	1.553	4.8
^{102}Tc*	4 m	0.940	2.377	0.717	2.497	0.796	2.415	0.856	2.430	2.1
^{132}Sb	4 m	1.382	2.600	1.353	2.363	1.348	2.583	1.307	2.673	5.2
^{132}Sb*	3 m	1.300	2.631	1.272	2.492	1.305	2.631	1.197	2.728	3.7
^{135}I	7 h	0.369	1.647	0.360	1.575	0.365	1.593	0.367	1.645	2.3
^{136}I*	46 s	2.130	2.000	2.148	2.145	2.126	2.137	1.760	2.942	18.6
^{136}I	83 s	1.968	2.378	1.980	2.394	2.035	2.479	1.760	2.942	10.4
^{140}Xe	14 s	1.181	1.210	1.223	1.117	1.139	1.152	1.230	1.150	3.3
^{140}Cs	64 s	1.649	2.300	1.739	2.105	1.703	2.285	1.429	2.791	12.4
^{140}La	40 h	0.548	2.331	0.531	2.316	0.620	2.319	0.545	2.312	0.4

Fig. 1. Experimental total energy emission rate following an instantaneous pulse of thermal-neutron fissions of ^{235}U, ^{239}Pu, and ^{241}Pu (ref. 1). The abscissa, t, is the time after a pulse of fissions. The ordinate is a quantity derived by obtaining f(t) and then multiplying it by t. The units are a contraction of (MeV/sec)/(fission/sec). Experimental uncertainties for ^{239}Pu data (dashed line) are comparable to those shown for ^{241}Pu data. Experimental uncertainties for ^{235}U (solid line) are somewhat smaller.

Fig. 2. Example of experimental data for ^{241}Pu: energy spectrum, $E_\beta \times N(E_\beta)$ vs E_β, for short irradiation, waiting, and counting periods (ref. 7).

Fig. 3. Decay schemes of the decay of ^{137}Cs and $^{137}Ba^*$. All of the normally reported values for discrete or continuous variables have been determined for these decays and are exhibited in this figure. Energies are in keV. Intensities are in percent.

Fig. 4. ^{90}Y beta-ray spectrum. Data were obtained using a scintillation detector described in ref. 1. Calculations are for two choices of shape factor. The dot-dash line represents the calculation using the allowed shape. The solid line represents the calculation using the shape factor for a first-forbidden unique transition.

Fig. 5. Compilation of log(ft) values for $I_\beta > 50\%$ transitions observed in fission-product decay for three types of transitions.

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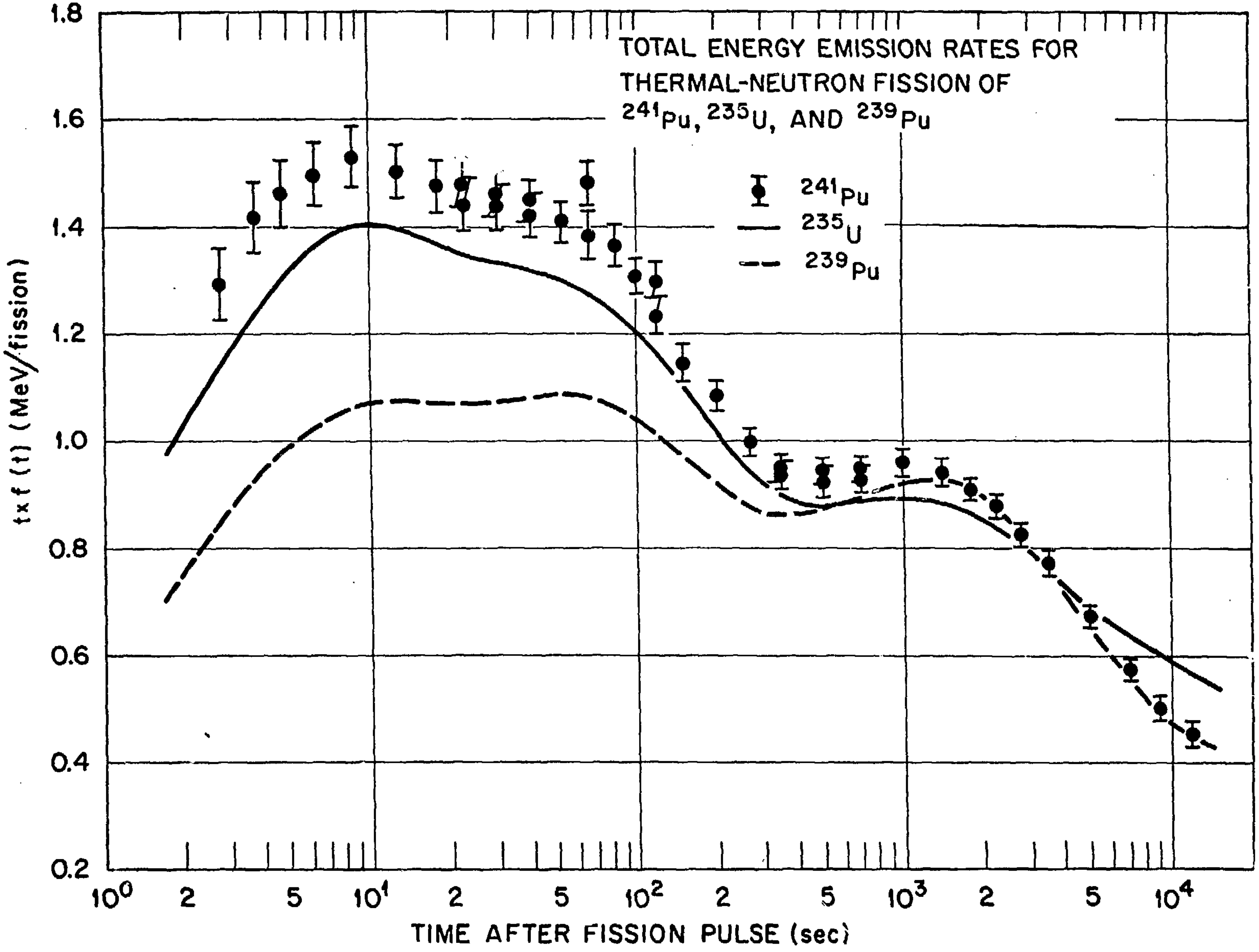

F2

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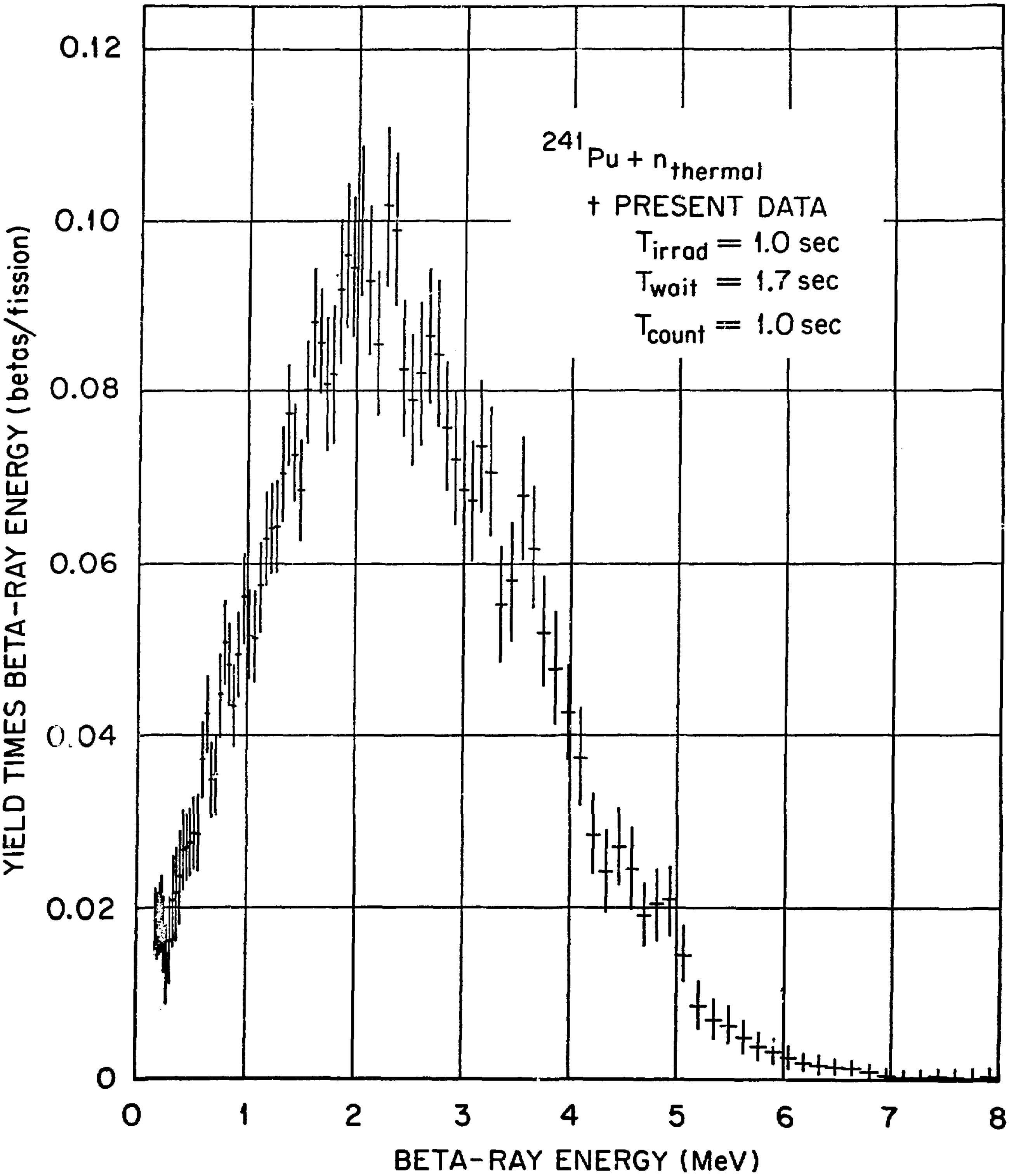

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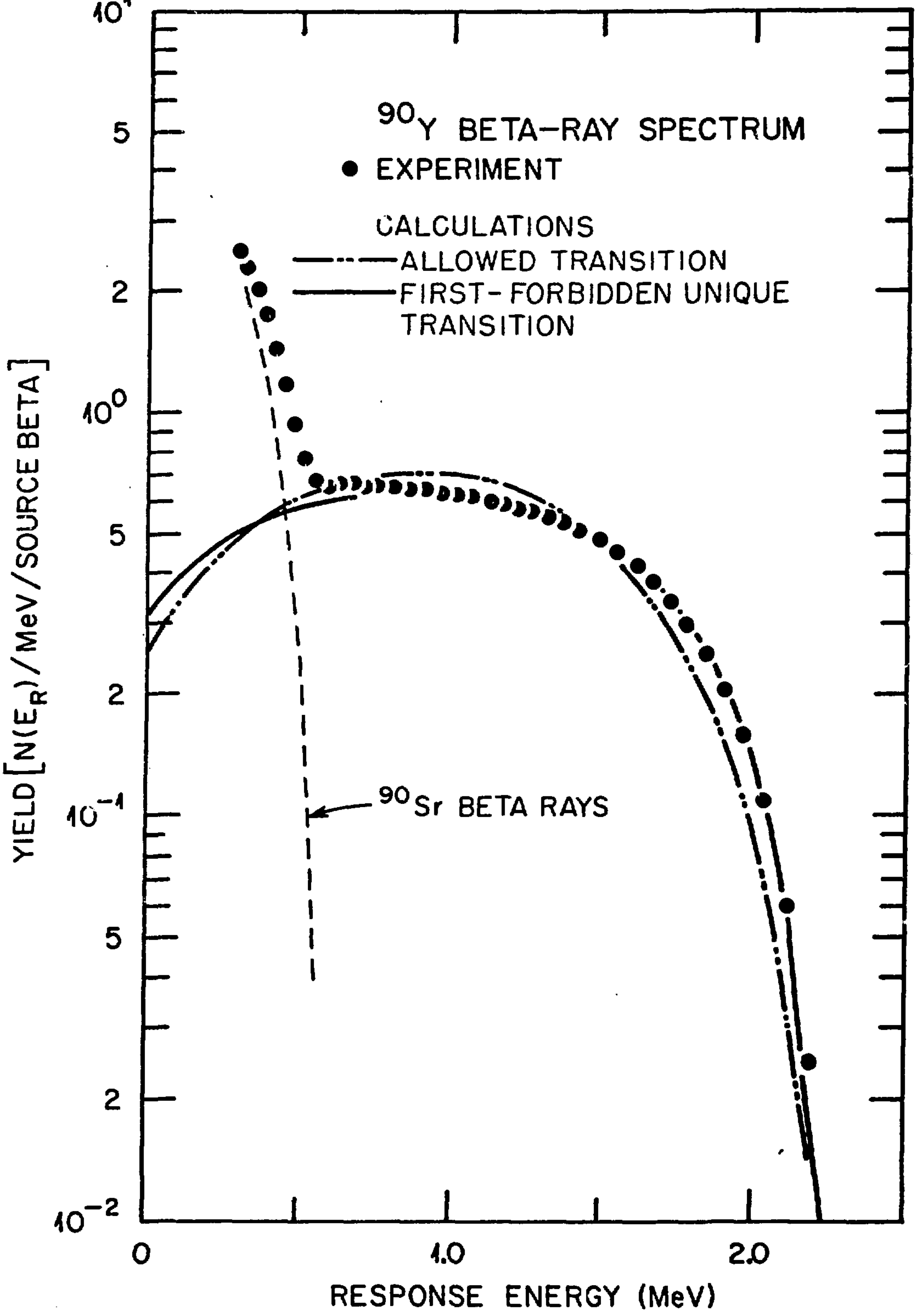

F 3

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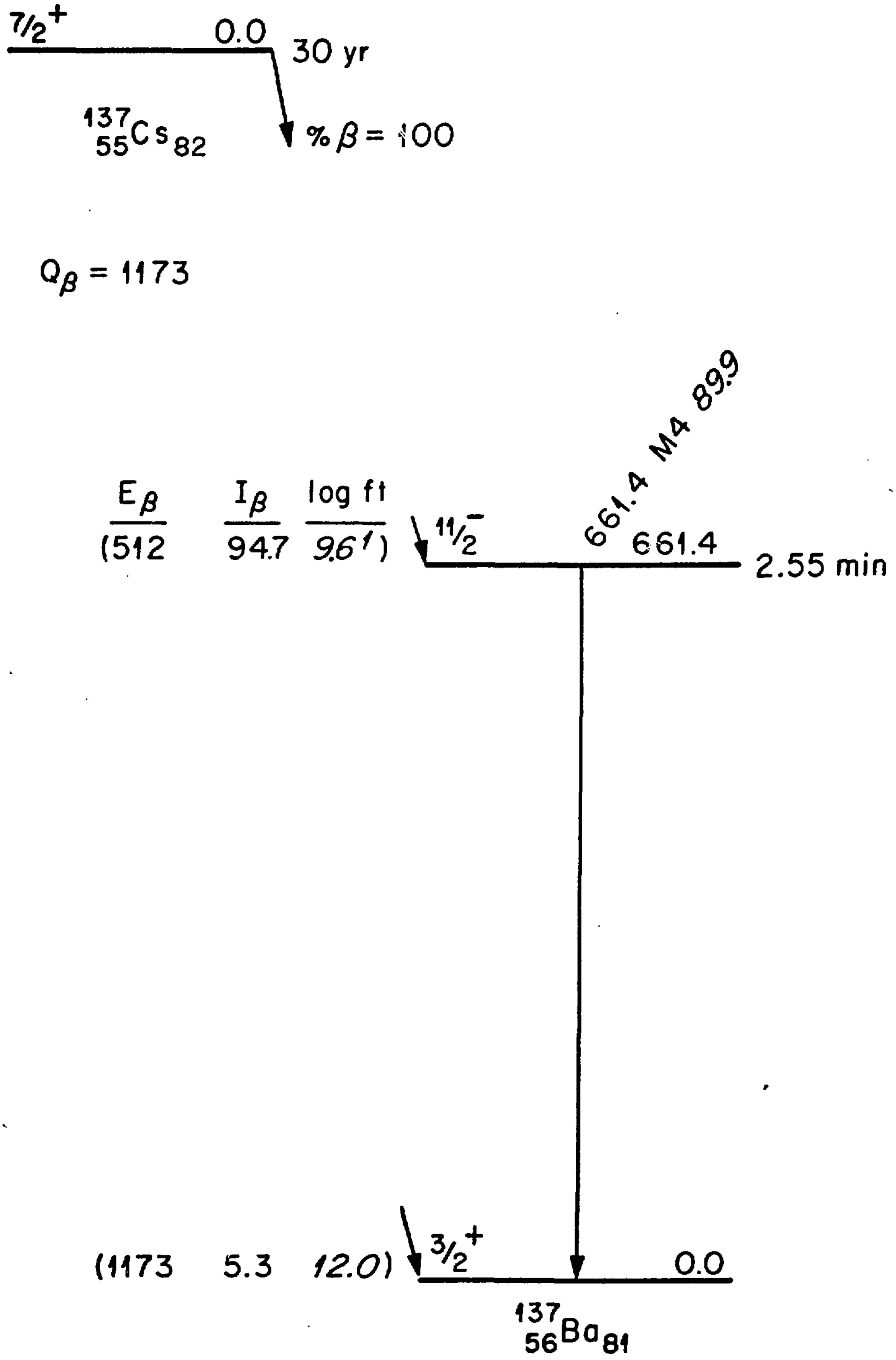

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