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Electron Antineutrino Spectrum for ^{235}U(n,f)

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The $\bar{\nu}_e$ spectrum has been computed for fission-product decay following a 30-d irradiation of ^{235}U by thermal neutrons. Estimated uncertainties lie in the range (7–15)% for $E_{\bar{\nu}} < 6$ MeV. Analysis relied on comparisons of calculated β-ray data with recently obtained experimental β-ray spectra. The $\bar{\nu}_e$ spectrum is softer than all other calculated $\bar{\nu}_e$ spectra. Cross sections (10^{-44} cm^2/fission) were calculated as $\sigma(\bar{\nu}_e + p \rightarrow n + e^+) = 58 \pm 3$, $\sigma(\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e) = 2.7 \pm 0.2$, and $\sigma(\bar{\nu}_e + d \rightarrow n + n + e^+) = 1.04 \pm 0.13$.

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In view of ongoing neutrino oscillation experiments with $\bar{\nu}_e$ fluxes from reactors, it is important to investigate the $\bar{\nu}_e$ spectrum, and, in particular, to establish the uncertainties associated with this spectrum. The $\bar{\nu}_e$ spectrum is obtained by "summation" methods. For each and every fission product a β-ray spectrum and an associated $\bar{\nu}_e$ spectrum are calculated. All of the spectra are weighted by the amount of the responsible fission product and then summed. The calculation requires as input data (a) fission-product yields and (b) nuclear data for β decay. Particularly for the short-lived fission products, hard experimental data are incomplete or nonexistent even for the extensively studied ^{235}U(n,f) fission system. Consequently, much of the "input data" must be obtained from estimates, usually assumptions based upon extrapolation from known radionuclide decay, and these assumptions are different for the two previously published calculations.[1,2] In these calculations comparisons were also made with β-ray spectra measured by Tsoulfanides, Wehring, and Wyman,[3] and the calculated[1,2] β-ray data disagree with the experimental data, by as much as a factor of 2 in the high-energy portion of the spectrum. In addition, high-precision experimental β-ray spectra recently obtained by Dickens and co-workers[4-6] substantially disagree with the earlier experimental data[3] for times <10 sec following fission, particularly for $E_\beta > 4$ MeV. These experimental β-ray data,[4-6] which were obtained for short times (2.2–13 950 sec) after fission of ^{235}U, were summed to provide a spectrum for the time conditions equivalent to a pulse of fissions, a 2.2 sec cooling time, and $t_{\text{count}} = 10\,798$ sec, and this β-ray spectrum is shown in Fig. 1. The data shown provide 82% of the total energy release expected for the conditions existing after 3 h of uniform thermal-neutron fission of ^{235}U. The calculational methods of Avignone and Greenwood[2] preclude comparison with these data, and it is not evident from the text of Davis *et al.*[1] whether their calculational methods can be so tested. In any event, because of the disagreements between the two calculations and between calculations and disparate experimental data, the

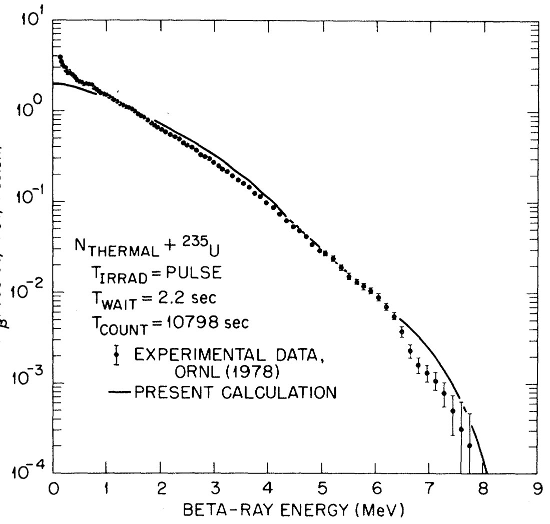

FIG. 1. β-ray spectrum 2.2 sec to 3 h following a pulse of thermal-neutron–induced fissions for ^{235}U. The solid line indicates results of the present calculation.

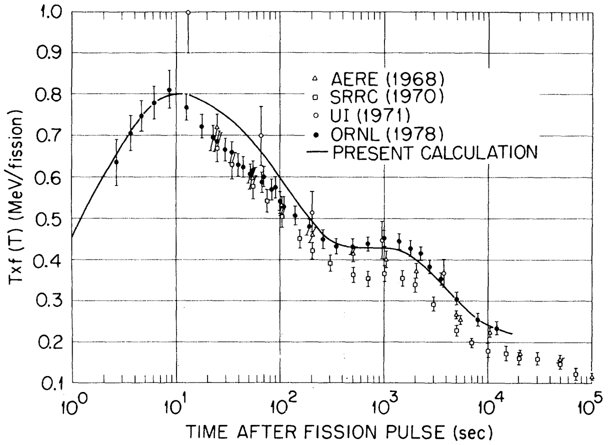

FIG. 2. β-energy emission rate following a pulse of thermal-neutron–induced fission of ^{235}U. The present calculation is compared with ORNL data (Refs. 4 and 5), University of Illinois (UI) data (Ref. 3), and the Atomic Energy Research Establishment (AERE) and Sperry Rand Research Center (SRRC) data (Ref. 13). The agreement between calculation and experiment is much better than observed with use of the ENDF/B-IV data base in a calculation, as shown in Fig. 6 of Ref. 4.

present investigation was undertaken.

It was decided to prepare an *independent* calculation, and use comparisons of calculated with experimental β-ray spectra of Ref. 6 as guides to determining the estimated β-ray decay of fission products not yet experimentally studied. The recent Rider and Meek evaluation[7] was used for all fission-product yields. The yield evaluation of Crouch[8] was also tested. For some unmeasured fission products, there are large differences among the values given in the two evaluations[7,8]; however, in aggregate the two evaluations result in similar calculated β-ray spectra. For ~270 fission products spectral decay information was obtained from the published literature[9]; for the remaining several hundred fission products an "average" β-ray energy $\langle E_\beta \rangle$ is given.[10] For fission products having spectral information, β-ray and $\bar{\nu}_e$ spectra were computed with use of an improved version of the code ELECSP.[5] The shapes of unique forbidden transitions, and of those nonunique forbidden transitions for which coefficients are available,[11] were correctly computed; for most transitions the allowed shape was computed for lack of more definitive information.

The first calculation was to determine the β-ray energy release [i.e., $\int E_\beta N(E_\beta) dE_\beta$] as a function of time following fission of ^{235}U. For each experimental set[4] of time conditions a total β-ray energy release datum was computed. These data were, in effect, differentiated to obtain the rate of β-ray energy release t sec following an instantaneous pulse of fissions. The rate function,[12] $f(t)$, decreases with t roughly as t^{-1}. Hence, for illustrative purposes it is common practice to show the "pulse" function as $tf(t)$, as done in Fig. 2. The experimental data include earlier data[3,13] as well as the data of Refs. 4–6. The important result is that for short times (< 10 sec) after fission there is excellent agreement, which means that *in aggregate* the $\langle E_\beta \rangle$ given in the present data file for short-lived fission products weighted by the fission-product yields are about right.

To provide an estimated β-ray spectral distribution for short-lived fission products lacking nuclear decay data, a simple prescription was followed. The assumption was made that the $\langle E_\beta \rangle$ given in the file was due to a single allowed transition.[14] This prescription may underestimate somewhat the amount of high-energy β rays in the calculated reactor spectrum *if* $\langle E_\beta \rangle$ is close to the true average value. However, the high-energy portion of the calculated spectrum shown in Fig. 1 agrees with or is larger than the experimental data, indicating that in aggregate the high-energy portion of the β-ray spectrum has not been underestimated. The calculation gives 6.4 MeV/fission for the total available β-ray energy available nearly immediately after fission which compares well with the Sher, Fiarman, and Beck[15] evaluation of 6.5 ±0.3 MeV/fission for ^{235}U(n_{thermal}, f).

A $\bar{\nu}_e$ spectrum was calculated corresponding to that expected following a 30-d, uniform n_{thermal} irradiation of ^{235}U, ignoring fuel depletion and nondecay gain or loss of fission products. The uncertainties associated with the present spectrum were obtained from (a) uncertainties in the β-ray measurements ($<5\%$ except for largest E_β), (b) estimates of $\Delta\bar{\nu}_e$ due to a moderate lack of agreement for some E_β as shown in Fig. 1, and (c) the uncertainties in the contributions due to short-lived unknown fission products conservatively estimated as 100% of their contribution to the $\bar{\nu}_e$ spectrum. The contribution of the short-lived ($T_{1/2} < 2$ sec) fission products lacking experimental decay data for the unmeasured time interval 0–2.2 sec is ~0.10 MeV/fission. A complete covariance matrix was developed and was used to determine individual uncertainties $\Delta N_{\bar{\nu}_e}(E_{\bar{\nu}_e})$. For comparison, the estimated uncertainties of Davis *et al.*[1] and Avignone and Greenwood[2] are based on plausibilities of the methods, calculational assumptions, and input data (see Table I).

From this $\bar{\nu}_e$ spectrum several integral quantities were determined. The $\bar{\nu}_e$ energy release for $E_{\bar{\nu}} \leq 8.25$ MeV is 8.61 ± 0.69 MeV/fission, which compares with 8.8 ± 0.3 MeV/fission from the Sher, Fiarman, and Beck[15] evaluation. Cross sections (10^{-44} cm^2/fission) were calculated as $\sigma(\bar{\nu}_e + p \rightarrow n + e^+) = 58 \pm 3$, $\sigma(\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e) = 2.66 \pm 0.16$, and $\sigma(\bar{\nu}_e + d \rightarrow n + n + e^+) = 1.04 \pm 0.13$ with use of published[1,16] formulas for the $\sigma(E_{\bar{\nu}})$ for the three reactions.

TABLE I. Equilibrium electron-antineutrino spectra for thermal-neutron fission of ^{235}U.

$E_{\bar{\nu}}$ (MeV)	$N(\bar{\nu}_e)$/MeV/fission Davis et al.[a] (Ref. 1)	 Avignone,[b] Greenwood (Ref. 2)	 Present Results[a]
1.0	2.23 ± 0.22	2.12 ± 0.03	2.22 ± 0.11
1.5	1.56 ± 0.16	1.62 ± 0.03	1.62 ± 0.08
2.0	1.16 ± 0.12	1.35 ± 0.02	1.26 ± 0.09
2.5	0.819 ± 0.096	1.04 ± 0.02	0.88 ± 0.10
3.0	0.593 ± 0.081	0.769 ± 0.013	0.657 ± 0.107
4.0	0.273 ± 0.045	0.349 ± 0.011	0.296 ± 0.025
5.0	0.103 ± 0.021	0.139 ± 0.007	0.092 ± 0.008
6.0	0.035 ± 0.008	0.0493 ± 0.0030	0.0286 ± 0.0036
7.0	0.0101 ± 0.0027	0.0150 ± 0.0011	0.0093 ± 0.0047
8.0	0.0019 ± 0.0006	0.0031 ± 0.0003	0.0016 ± 0.0008

[a] For 30-d irradiation.

[b] "Secular" equilibrium.

We note in particular that the value of $\sigma(\bar{\nu}_e + d \rightarrow n + n + e^+)/\sigma(\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e)$ is within uncertainty in agreement with those computed using the Davis *et al.*[1] and the Avignone and Greenwood[2] spectra. For comparison with neutrino oscillation experiments[17] it must be kept in mind that the *total* experimental antineutrino spectrum also includes $\bar{\nu}_e$ from, e.g., Pu(n,f), activation of structural and shielding materials, etc. The important contributions of the present study are for the first time (a) to place the calculational methods and data base to calculate both β-ray and $\bar{\nu}_e$ spectra for ^{235}U(n,f) on a firm experimental basis, (b) to provide a reliable set of uncertainties, and (c) to indicate through data comparisons shown in Figs. 1 and 2 where further studies of the basic nuclear data are needed.

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Influence of the Static Deformation of ^{7}Li on the ^{7}Li-^{51}V Total Reaction Cross Section

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The energy dependence of the reaction cross section and the corresponding tensor analyzing power has been measured for the system ^{7}Li-^{51}V by two different methods. The tensor analyzing powers observed can be interpreted in a sharp-cutoff model as caused entirely by the static deformation of the ^{7}Li projectiles.

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The role of deformation, both static and dynamic, in heavy-ion collisions is at present an eagerly discussed topic. The extent to which the total reaction or fusion cross section in a heavy-ion interaction is affected by the deformation of one of the reaction partners has been investigated recently both theoretically and experimentally.[1-4] Although there is strong experimental evidence that the reaction cross section depends on the deformation of the reaction partners, a clear-cut case does not exist at present. In all experiments up to now unpolarized projectiles and targets have been used, mostly with zero spin. The influence of the intrinsic nuclear deformation can be extracted by comparing excitation functions of the fusion or of the reaction cross section of one nucleus with a variety of isotopes possessing different intrinsic deformations. In such studies large differences in the fusion cross section of various isotopes have been observed near the Coulomb barrier. Model calculations which consider the intrinsic deformation as the only degree of freedom have been applied successfully to fit the data. The crucial point of these model calculations is the assumed mass dependence of the nuclear interaction.

To detect the influence of the deformation on the fusion or the total cross section in a clear-cut manner one aligned reaction partner with a nonvanishing spectroscopic quadrupole moment is required. If the spins of such nuclei are aligned, the spectroscopic quadrupole moments are aligned as well. Information regarding the influence of the spectroscopic deformation on the total reaction or fusion cross section can then be obtained by comparing the results of the experiments with aligned and unpolarized nuclei. Experiments along this idea have been performed to show the