Report: DOE/ER/40723-4

BETA AND GAMMA DECAY HEAT MEASUREMENTS BETWEEN 0.1s - 50,000s FOR NEUTRON FISSION OF ^{235}U, ^{238}U AND ^{239}Pu

Final Report

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ABSTRACT

This is a final reporting on the completion of separate beta and gamma decay heat measurements following neutron fission of ^{235}U, ^{238}U and ^{239}Pu and on cumulative and independent yield measurements of fission products of ^{235}U and ^{238}U. What made these studies unique was the very short time of 0.1s after fission that could be achieved by incorporating the helium jet and tape transport system as the technique for transporting fission fragments from the neutron environment of the fission chamber to the low-background environment of the counting area. This capability allowed for the first time decay heat measurements to extend nearly two decades lower on the logarithmic delay time scale, a region where no comprehensive aggregate decay heat measurements had extended to. This short delay time capability also allowed the measurement of individual fission products with half lives as short as 0.2s. The purpose of such studies was to provide tests both at the aggregate level and at the individual nuclide level of our nation's evaluated nuclear data file associated with fission, ENDF/B-VI. The results of these tests are in general quite encouraging indicating the this data base generally predicts correctly the aggregate beta and aggregate gamma decay heat as a function of delay time for ^{235}U, ^{238}U and ^{239}Pu. Agreement with our measured individual nuclide cumulative and independent yields for fission products of ^{235}U and ^{238}U was also quite good although the present measurements suggest needed improvements in several individual cases.

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1. RESEARCH

A. INTRODUCTION

This final report summarizes aggregate decay heat measurements and individual fission product nuclide cumulative and independent yield measurements that have been both completed and analyzed. The research covered three separate areas of fission product studies:

- aggregate gamma energy distributions and decay heat of ^{235}U, ^{238}U and ^{239}Pu
- aggregate beta energy distributions and decay heat of ^{235}U, ^{238}U and ^{239}Pu,
- cumulative and independent yields of short-lived fission product nuclides of ^{235}U and ^{238}U

The primary reason for these studies was to provide tests for the nation's evaluated nuclear data file associated with fission, ENDF/B-VI[1], particularly extending down to very short delay times where no reliable measurements existed and where ENDF/B-VI is most uncertain. Dr. Talmadge England of Los Alamos National Laboratory, the evaluator for this file, has been a collaborator in these studies. This collaboration has also allowed for the timely transfer of our measurement results for the improvement of this data base.

This report will concentrate on the final results in the three areas described above. An earlier report (DOE/ER/40723-3) covering the period 6/1/92-12/31/94 presented the designs of the three spectrometers and their energy and response function calibrations. Measurements with the three spectrometers were also shown in this earlier report along with the unfolding programs that convert the aggregate gamma and beta spectra into energy distributions. The uniform transfer efficiency of fission fragments with the helium jet was also established in this earlier report. These details, which will not be repeated here, complement this final report and give essential background information. A reading of both reports will lead to a more complete understanding of what this research project encompassed.

This research program involved six graduate students and four faculty members. The research has produced 5 Ph.D. theses (2 in preparation) and 3 M.S. theses. To date there have been 6 refereed publications, 2 papers submitted for publication, and 34 American Physical Society presentations. There will be 7 additional papers submitted for publication (three will be presented at the international conference in Trieste, Italy in May, 1997). Abstracts of the conference papers and the APS presentations are given in section 4. The papers are included in section 5 and copies of the theses separately accompany this final report.

B. AGGREGATE GAMMA-RAY SPECTRA AND DECAY HEAT FOR ^{235}U, ^{238}U, ^{239}Pu

Aggregate gamma-ray energy spectra have been measured for fission products resulting from the thermal neutron fission of ^{235}U and ^{239}Pu, and from the fast neutron fission of ^{238}U. The measurements were performed using a beta-gated 5"x5" NaI(Tl) spectrometer and covered an energy range of 0.1-8.0 MeV. Spectra were taken over a decay time range of 0.1-40,000s, with measurements made at approximately three decay times per decade. After background subtraction each spectrum was unfolded using the programs NGRC[2] and CRSUP[2] (described in the accompanying 3-year progress report) to obtain the true gamma-ray energy distribution at a particular mean decay time. An average gamma-ray energy was calculated for each energy distribution. The average energy was corrected for the low energy cutoff (typically 50-85keV) of our NaI(Tl) spectrometer to obtain a corrected average gamma-ray energy at each mean decay time. Fig.B1 shows a plot of corrected average gamma-ray energies as a function of mean decay time determined from our study of the thermal neutron fission of ^{239}Pu. The average energies are in excellent agreement with those from an earlier study by Dickens et al.[3] over the entire decay-time range of overlap.

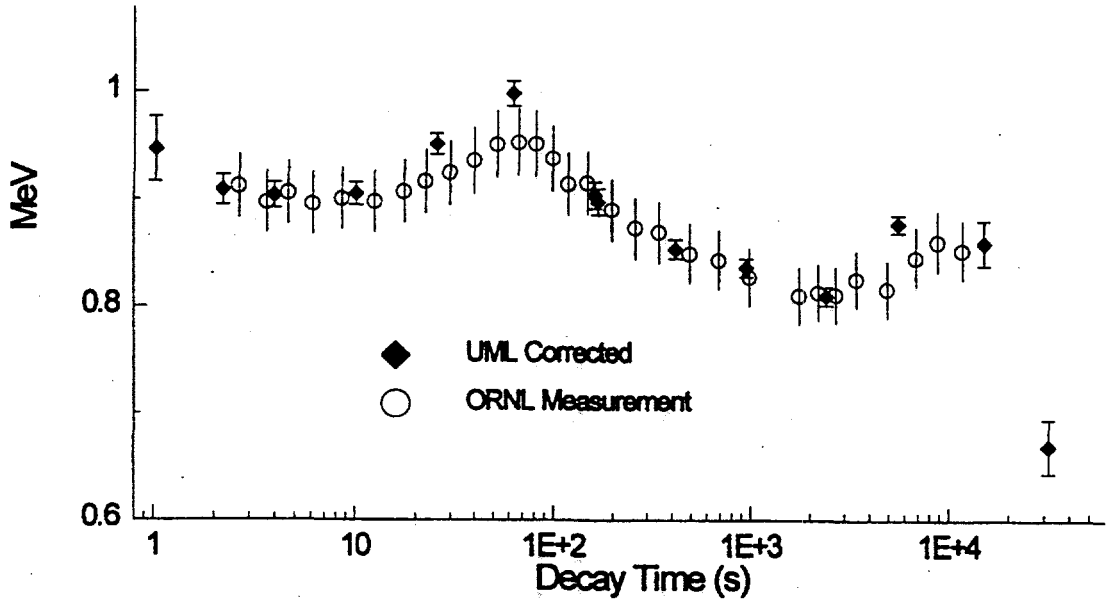

Figure B1. Average aggregate gamma-ray energy following thermal neutron fission of ^{239}Pu.

The gamma-ray decay heat as a function of decay time can be determined from the average gamma-ray energy, measured gamma-to-beta activity ratio and the measured beta activity as a function of time. The gamma-to-beta ratio for ^{239}Pu is plotted in Fig.B2, where it is compared with the corresponding results of Dickens et al.[3] Because the ratio depends on the absolute efficiency of the gamma-ray spectrometer, the UML ratio has been renormalized to give the best agreement with the ORNL study. The agreement is excellent except for decay times beyond 1,000s, where the UML ratio is significantly lower than the ORNL ratio. At present we have no explanation for this discrepancy, which also affects the ^{239}Pu decay heat results at these longer times.

The relative beta activity as a function of decay time was measured for ^{235}U, ^{238}U and ^{239}Pu. The beta activity of ^{239}Pu is listed in Table B1. The corresponding gamma-ray decay heat was obtained by forming the product of the average gamma-ray energy, the gamma-to-beta ratio and the beta activity. Since the noble gases transferred by the helium jet are not retained by the tape transport system, these results represent the gamma decay heat excluding noble gases. CINDER[4,5] calculations were used to estimate the noble gas contribution at each decay time. Correction factors were thus generated to account for the loss of noble gases, and these factors along with the corrected gamma-ray decay heat for ^{239}Pu are presented in Table B1.

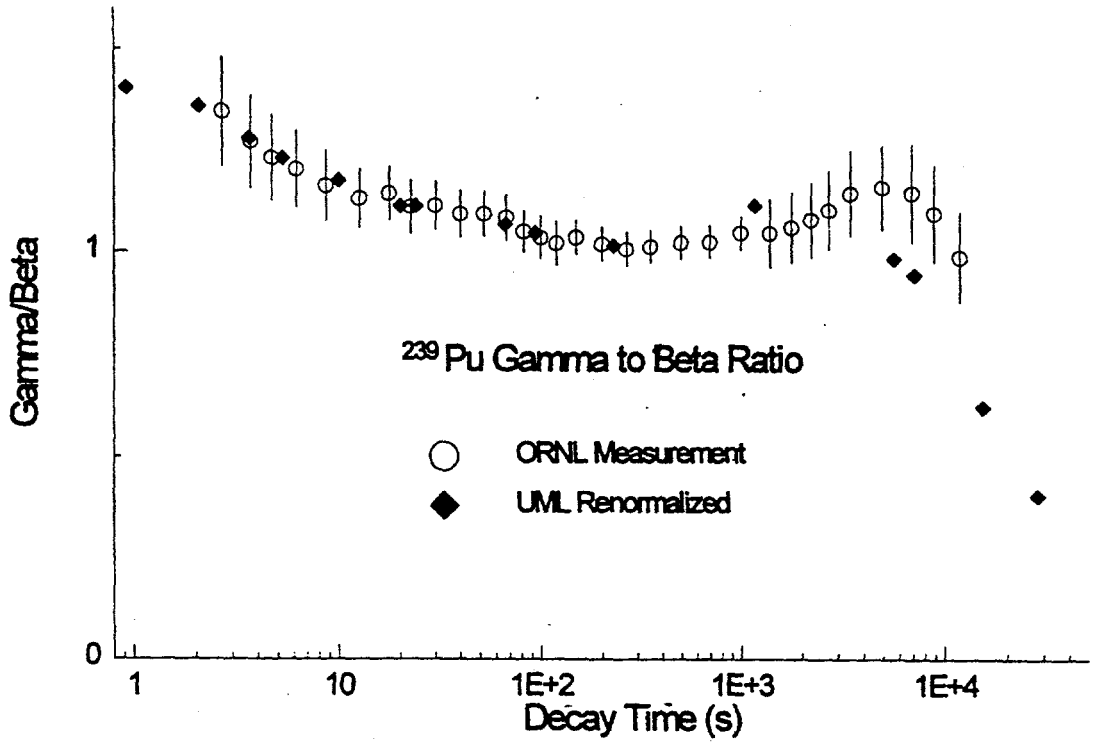

Figure B2. Gamma to beta ratio comparison of our measurements with those at ORNL.

The corrected gamma-ray decay heats for ^{235}U, ^{238}U and ^{239}Pu were multiplied by the decay time and plotted versus decay time in Figs. B3, B4 and B5, respectively. The present results are compared with CINDER calculations and with earlier ORNL[3,6] and YAYOI[7-9] measurements. The agreement is generally good except at the shortest and longest decay times.

At the shortest decay times there are no earlier measurements for comparison, but our decay heat values are somewhat higher than the CINDER calculations. At the the shorter decay times the ENDF/B-VI fission-product data base used in the CINDER calculations is supplemented by theoretical estimates based on the Gross Theory[10,11] of beta decay and a gamma-ray cascade model[12] for estimating the gamma-ray spectra for many unmeasured fission products. Our measurements suggest that the discrepancy lies mainly with the aggregate gamma-to-beta activity ratio, rather than with the average gamma-ray energy or the relative beta activity.

The present measurements are significantly lower than the CINDER calculations and the ORNL and YAYOI measurements for decay times longer than 1,000s. This systematic deviation suggests a possible problem in the present measurements for longer decay times. In this region it was found that the discrepancy is due alomost entirely to our lower value of gamma-to-beta activity ratio. It was suspected that this ratio may be sensitive to the beta-gamma gating condition used in the measurements. However, a modification greatly relaxing the coincidence requirements showed no significant change in the ratio. At present we have no plausible explanation for the discrepancy at longer decay times. Full details for the ^{238}U and ^{239}Pu cases can be found in the accompanying thesis of Edward Seabury.

Table B1 ^{239}Pu beta activity and decay heat

Decay Time (s)	Activity*time (fiss^{-1})	Decay Heat*time (MeV/fiss)	Correction Factor (Total/No Nobles)
1.04	0.161 (0.88)	0.259 (3.7)	1.042
2.25	0.243 (0.88)	0.367 (2.5)	1.044
4.03	0.294 (0.88)	0.418 (2.3)	1.049
10.2	0.341 (0.44)	0.460 (2.1)	1.063
25.9	0.351 (0.44)	0.486 (2.1)	1.097
63.7	0.362 (0.44)	0.527 (2.1)	1.123
165	0.352 (0.44)	0.446 (2.3)	1.156
170	0.350 (0.44)	0.445 (2.2)	1.156
425	0.344 (0.44)	0.428 (2.0)	1.165
968	0.383 (0.44)	0.503 (2.1)	1.179
2470	0.366 (0.44)	0.484 (2.1)	1.249
5710	0.241 (1.1)	0.296 (2.2)	1.250
15400	0.199 (1.1)	0.135 (3.1)	1.133
31900	0.204 (1.1)	0.0731 (4.3)	1.137

Uncertainties given as a percentage in parentheses

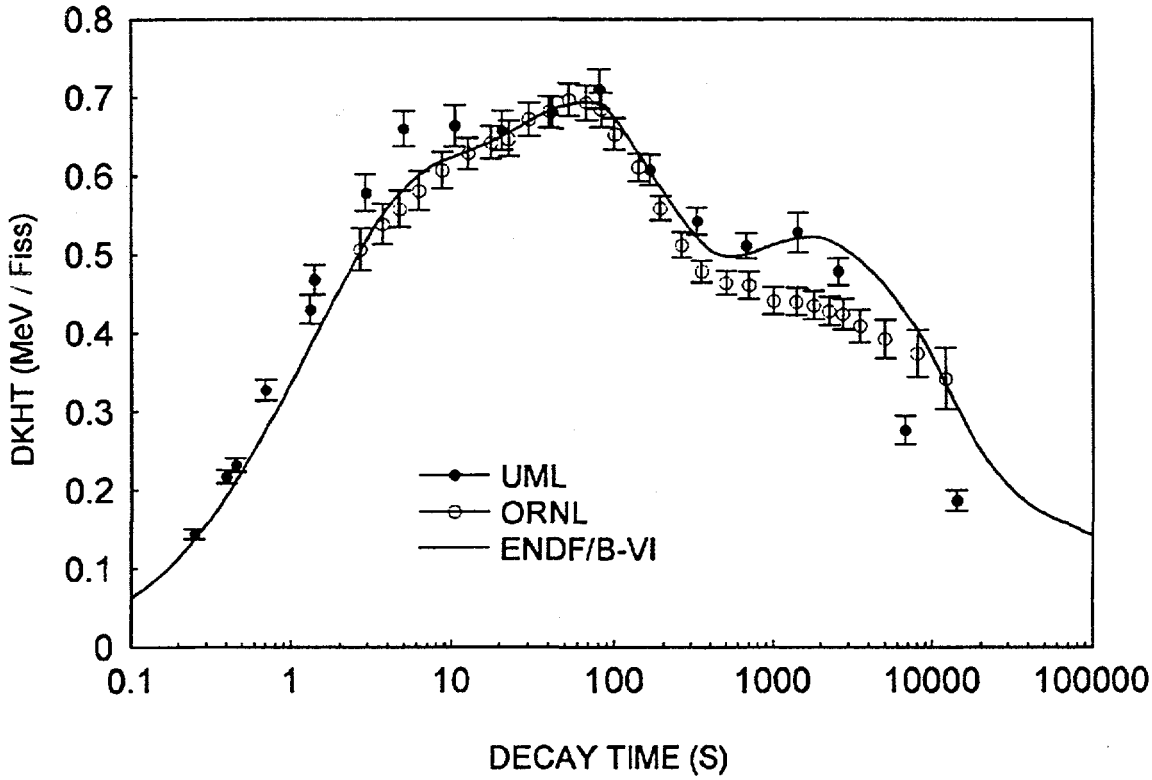

Figure B3. Comparison of total aggregate gamma decay heat following ^{235}U fission.

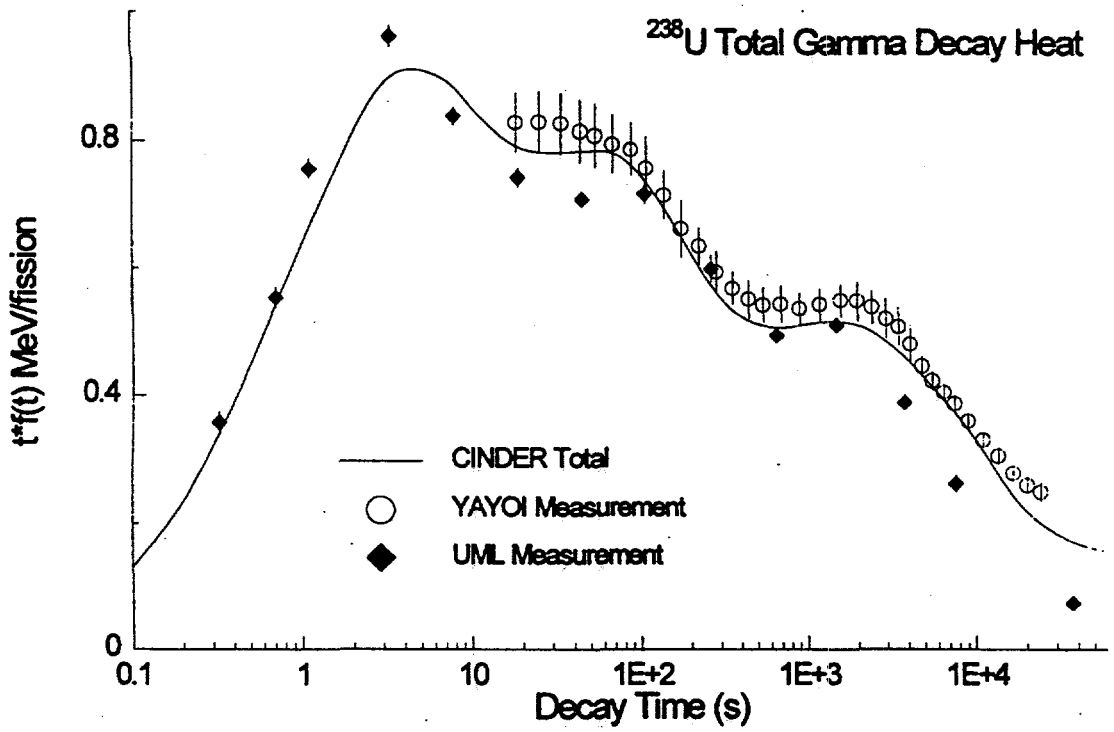

Figure B4. Comparison of the total aggregate gamma heat following fission of ^{238}U.

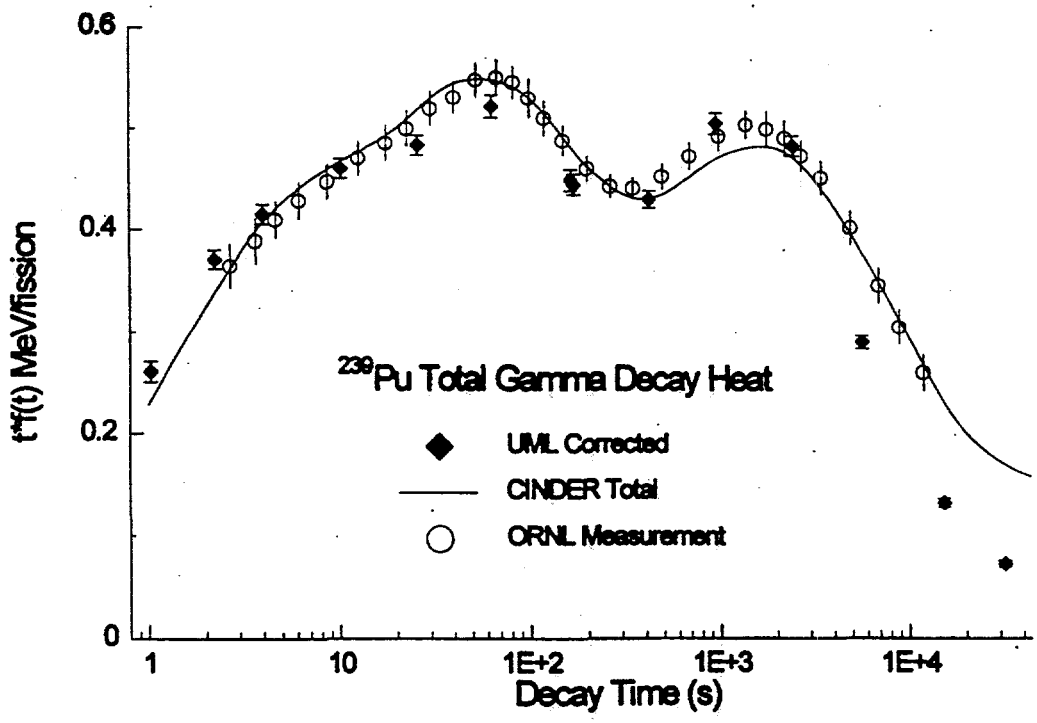

Figure B5. Comparison of total aggregate gamma decay heat following fission of ^{239}Pu.

C. AGGREGATE BETA SPECTRA AND DECAY HEAT OF ^{235}U,^{238}U,^{239}Pu

Beta energy spectra have been measured for the aggregate fission products resulting from thermal neutron fission of ^{235}U and ^{239}Pu, and from fast neutron fission of ^{238}U. The beta spectrometer consisted of a 3"x3" plastic scintillator, gated by an optically isolated thin-disk scintillator mounted on its surface for gamma-ray suppression. Measured spectra covered a beta energy range of 0.15-8.00 MeV and spanned a decay time range of 0.4-40,000s in steps of approximately 3 decay times per decade. After subtraction of background, internal-conversion electron peaks and beta-plus-gamma sum events, each spectrum was unfolded using the program FERD-PC[13] (described in the accompanying 3-year progress report) to obtain the beta energy distribution for a particular mean decay time. A typical unfolded beta spectrum obtained from fission products of ^{235}U is shown in Fig.C1. Our results are in good agreement with those from the earlier study by Dickens et al.[6], except at energies below 1MeV where our distribution is significantly lower. Also shown in the figure is the beta spectrum calculated using the CINDER10 and SPEC5[14] programs run on the LANL Cray computer. ENDF/B-VI fission-product data were used in the calculation. The calculated spectrum shows considerably higher yield in the high energy region than the measurements. Similar discrepancies were observed for all the fission-product beta spectra of ^{235}U measured at short decay times, as well as for the spectra obtained from ^{238}U and ^{239}Pu at short decay times. In this decay-time region ENDF/B-VI measured spectra have been supplemented by theoretical spectra calculated using the Gross Theory of beta decay. It appears that the theory overestimates the high-energy beta yield for large Q-value nuclei.

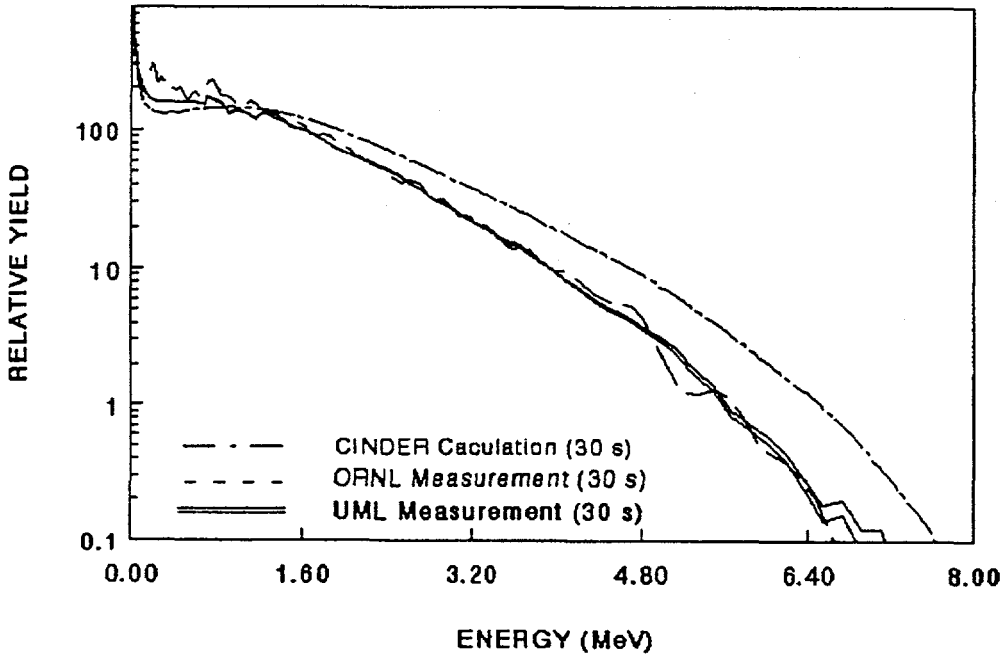

Figure C1. Comparison of UML unfolded ^{235}U beta spectrum with ORNL and CINDER values.

The average beta energy was calculated for each energy distribution, after correcting for the 150-keV cutoff of our spectrometer. For this correction the missing low-energy portion of each of our measured beta spectra was estimated using the CINDER10 and SPEC5 calculations for each decay time. The resulting average beta energies determined for ^{235}U, ^{238}U and ^{239}Pu are listed in Tables C1. Our results for ^{235}U and ^{239}Pu are compared with those of Dickens et al.[3,6] in Figs. C2 and C3. Both the ^{235}U and the ^{239}Pu average beta energies are generally in good agreement with the ORNL measurements.

Table C1. Average aggregate beta energies for ^{235}U, ^{238}U and ^{239}Pu.

^{235}U		^{238}U		^{239}Pu	
Decay Time(s)	Average Energy (MeV/Beta)	Decay Time(s)	Average Energy (MeV/Beta)	Decay Time(s)	Average Energy (MeV/Beta)
0.41	1.685	0.40	1.759	0.40	1.621
0.67	1.739	0.62	1.695	0.67	1.678
1.04	1.737	1.05	1.709	1.04	1.669
1.37	1.742	1.34	1.722	1.32	1.680
2.08	1.664	2.51	1.668	2.08	1.629
4.90	1.626	6.27	1.525	4.79	1.549
12.7	1.512	10.0	1.441	12.0	1.442
30.4	1.241	23.9	1.302	30.6	1.195
79.0	1.156	46.4	1.202	75.0	1.081
180	1.058	102	0.966	186	0.959
440	0.892	330	0.943	439	0.844
1060	0.877	960	0.828	1030	0.850
2820	0.823	1930	0.805	2380	0.785
6770	0.718	2040	0.813	6200	0.675
14400	0.712	4080	0.700	12140	0.587
26900	0.632	6680	0.681	20700	0.600
40000	0.618	9400	0.646	41070	0.542
		18000	0.609		
		31600	0.588		

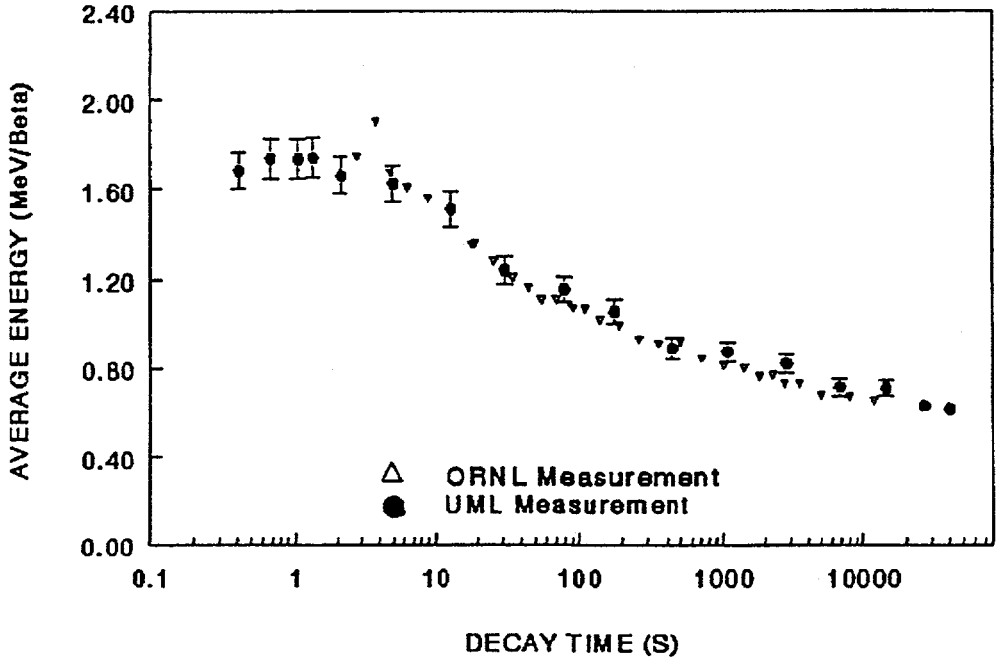

Figure C2. Comparison of average aggregate beta energies following the fission of ^{235}U.

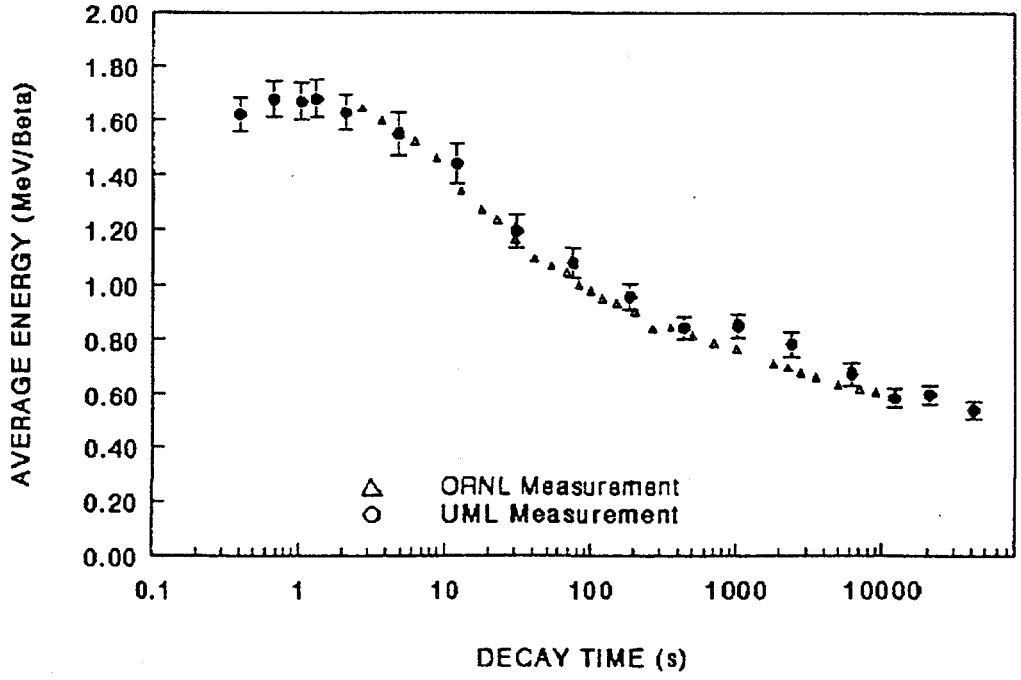

Figure C3. Comparison of average aggregate beta energies following the fission of ^{239}Pu.

The relative beta decay heat as a function of decay time after fission was determined by multiplying the average beta energy by the corresponding relative beta activity. Figs. C4-C6 show the relative beta activity of ^{235}U, ^{238}U and ^{239}Pu respectively compared with CINDER10 summation calculations based on ENDF/B-VI fission product data. In each case the measured activity has been renormalized to give the best overall agreement with the CINDER10 calculations. In general the agreement is good except for decay times longer than 1000s, where the current measurements are significantly lower than the CINDER10 calculation for each of the three fissionable isotopes. At shorter decay times the only observed discrepancy was in the ^{235}U activity for times less than 10s where our measurements are somewhat higher than the predicted activity.

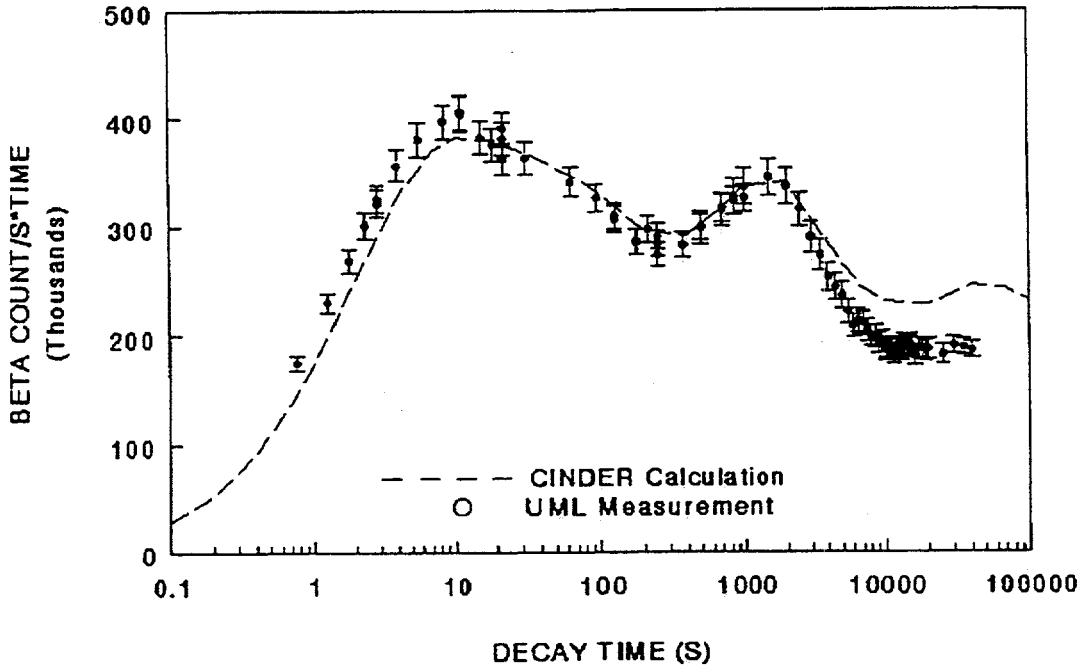

Figure C4. Comparison of beta activity multiplied by decay time plotted vs decay time for ^{235}U case.

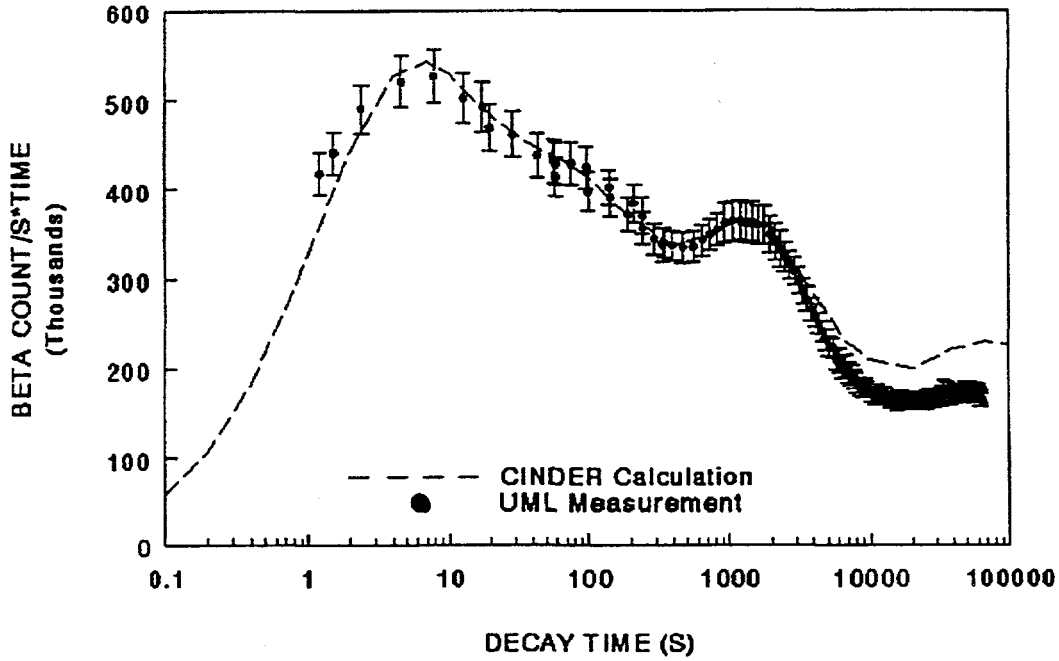

Figure C5. Comparison of beta activity multiplied by decay time plotted vs decay time for ^{238}U case.

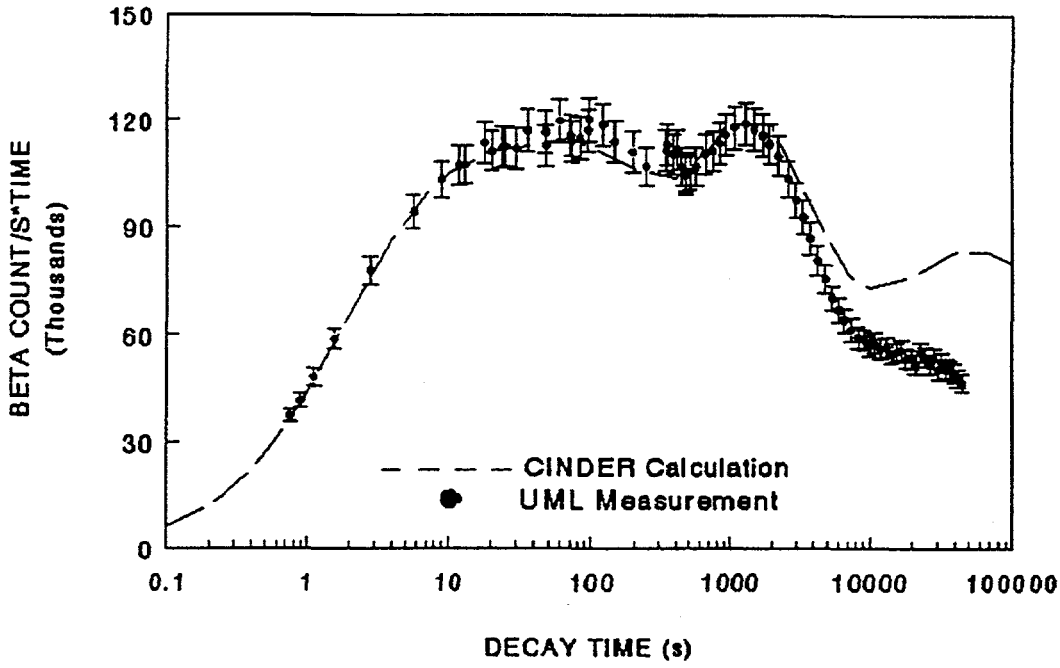

Figure C6. Comparison of beta activity multiplied by decay time plotted vs decay time for ^{239}Pu case.

The beta decay heat was obtained by forming the product of the average beta energy times the relative beta activity. Again the result was corrected for loss of noble gases. The corrected beta heat for ^{235}U, ^{238}U and ^{239}Pu multiplied by the decay time is plotted versus decay time in Figs. C7-C9, respectively. The results of the present study are compared with the earlier ORNL measurements[3,6] in the case of ^{235}U and ^{239}Pu and with the YAYOI beta decay heat results[7-9] for ^{238}U. The present results have been normalized to give the best overall agreement with the CINDER10 calculations. For ^{235}U and ^{239}Pu our results are in excellent agreement with those of ORNL throughout their region of overlap. Excellent agreement was also observed between our ^{238}U beta decay heat and that reported in the YAYOI study.

For ^{235}U and ^{239}Pu both our measurements and the ORNL results are in excellent agreement with the CINDER10 calculation everywhere, except in the vicinity of 1000s decay time where both measurements suggest a slightly higher value for the beta decay heat. The UML and YAYOI beta decay heat measurements for ^{238}U are also in excellent agreement with CINDER10 calculations, with only a similar slight discrepancy in the vicinity of 1000s. It is interesting to note that even in regions where our measured relative beta activity disagrees with CINDER10, our average beta energies disagree in the opposite direction to give excellent overall agreement in the beta decay heat. Full details of the beta decay heat study will be available in the Ph.D. thesis of Shengjie Li, now in preparation.

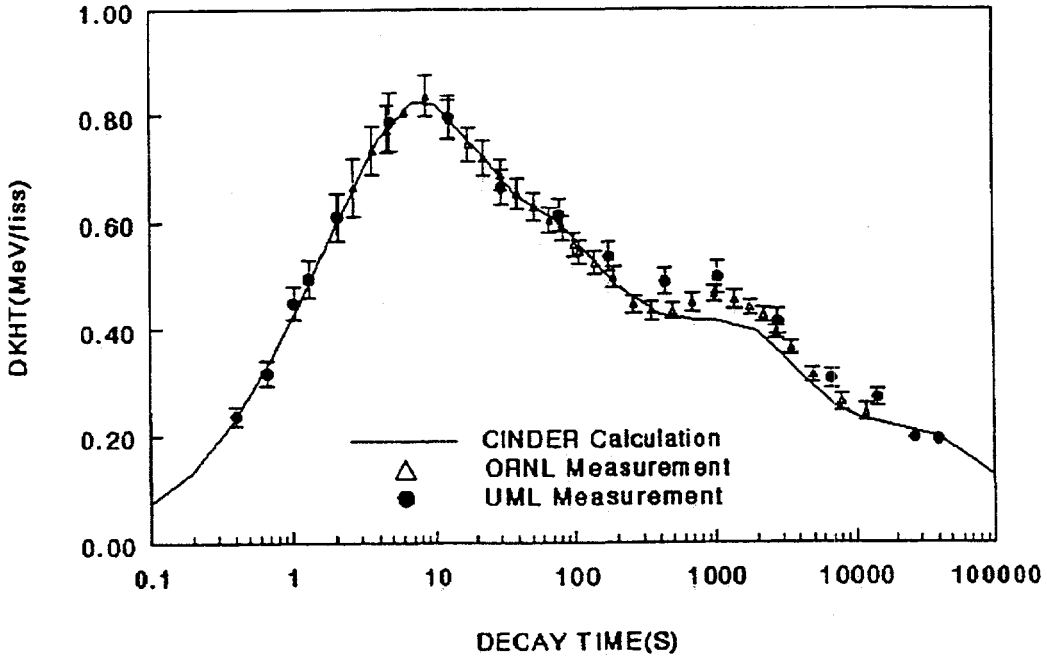

Figure C7. Comparison of total aggregate beta decay hear following ^{235}U fission.

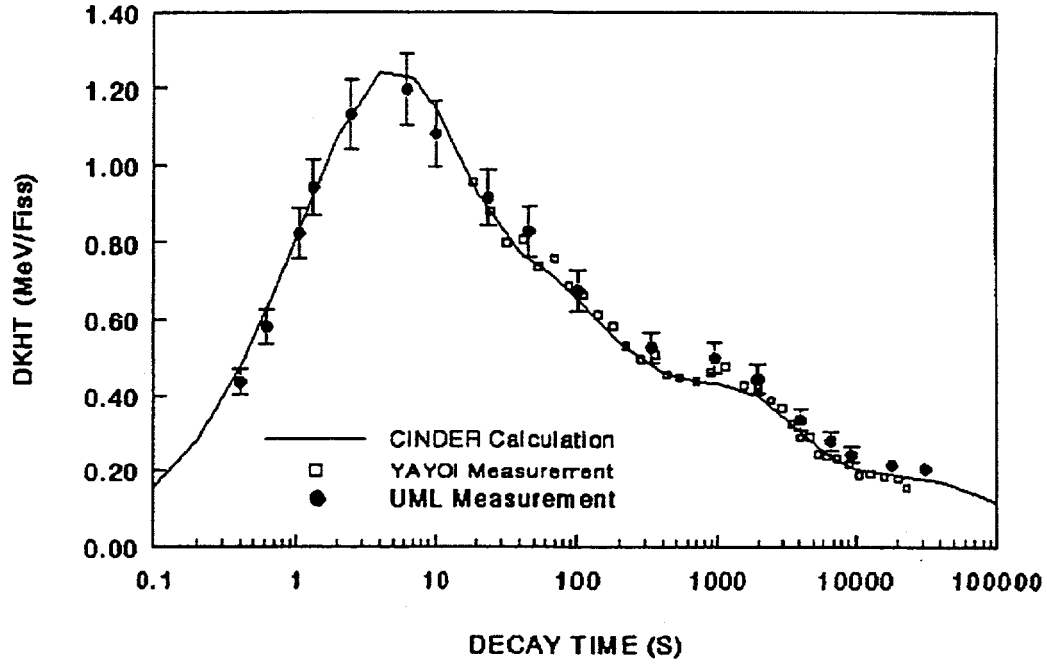

Figure C8. Comparison of total aggregate beta decay heat following fission of ^{238}U.

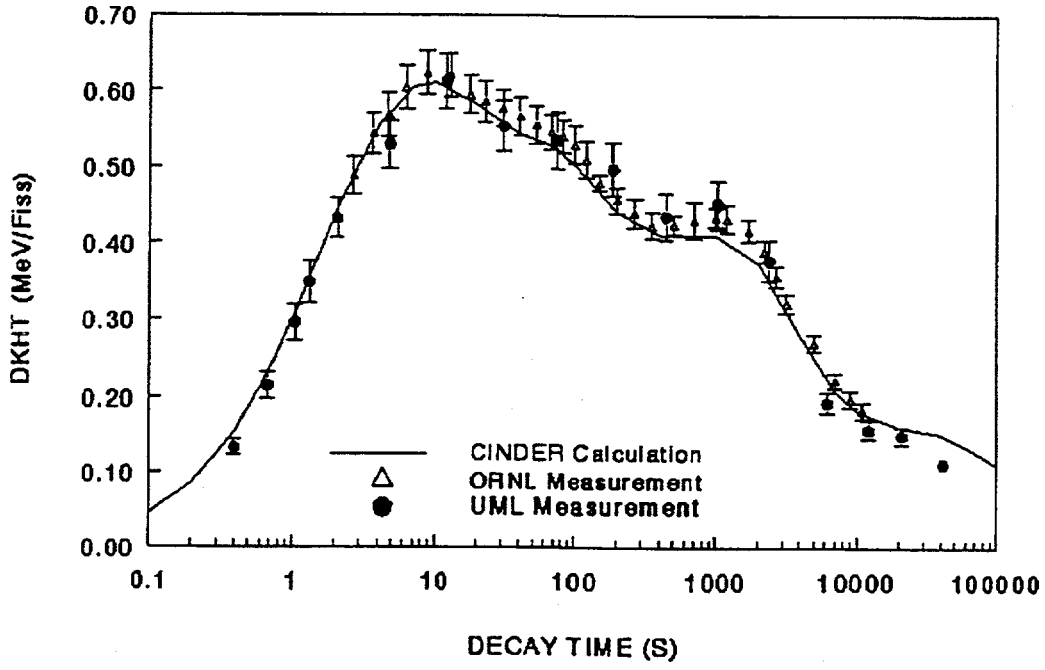

Figure C9. Comparison of total aggregate beta decay heat following fission of ^{239}Pu.

D. INDEPENDENT AND CUMMULATIVE YIELDS

Measurement results are summarized here of the independent yields which arise directly from the fission process and of the cumulative yields which also include the beta chain contributions. These results are compared to ENDF/B-VI values.

i) Short-lived fission product nuclides of ^{235}U

Measurements of high-resolution gamma-ray spectra, following the thermal neutron fission of ^{235}U, have been made with a Compton suppressed, beta-gated high purity germanium detector at the UMASS Lowell Van de Graaff facility. The gamma spectra were measured at delay times ranging from 0.2s to nearly 10,000s following rapid transfer of the fission fragments with a helium-jet system. On the basis of known gamma transitions, forty isotopes have been identified and studied. By measuring the relative intensities and lifetimes of these transitions and using their published beta branching ratios, the relative probabilities for direct production of the various precursor nuclides have been calculated. Metastable and ground state yields have been measured in several cases. The division between metastable and ground-state yields tends to be quite uncertain in the ENDF/B-VI compilation and therefore the current measurements are an important contribution to this file. Elemental yields for rubidium, cesium, strontium and barium fission products where compared to those in ENDF. Even-odd effects in the distributions of partial elemental yields were also clearly observed. The full paper submitted to the Physical Review C is included in Section 5 of this report and therefore the details will not be repeated here.

ii) Short-lived fission product nuclides of ^{238}U

Measurements of gamma-ray spectra following fast neutron fission of ^{238}U with the HPGe system described above were performed in a fast-neutron port on the UMASS Lowell Research Reactor. The cadmium shielded fission chamber resided near the core and the counting system was located at a nearby shielded area. The gamma spectra were measured over delay times ranging from 0.3s to 4,000s. Precursor nuclides were identified based on the gamma-ray energies, relative intensities and the intensities' time dependence (due mainly to the precursor half life).

Table D1 lists 63 independent yields and 63 cumulative yields resulting from our measurements and compares them to ENDF/B-VI. Our experimental values typically have uncertainties of 10% or less while the ENDF values have typical uncertainties of 25% or more. Only 28% of the nuclides in this study have previously measured independent and cumulative yield values listed in ENDF with the remainder based solely on model calculations. The overall agreement with ENDF/B-VI is reasonable, with 57% of the values falling within one standard deviation (68% expected) and 81% falling within two standard deviations (95% expected). In these tables 8 ground and 7 metastable state yields have been measured. Metastable/ground-state yield values are often not well known in ENDF and therefore

Table D1. UML independent and cumulative yields for ^{238}U fission compared with ENDF/B-VI.

Nuclide	$T_{½}$	Independent Yield Experimental	Independent Yield ENDF	Expt/ENDF	Cumulative Yield Experimental	Cumulative Yield ENDF
^{89}Br	4.4 s	2.601 ± 0.263	1.623 ± 0.519	1.60 ± 0.54	2.909 ± 0.405	1.944 ± 0.447
^{89}Rb	15 m	0.516 ± 0.045	0.089 ± 0.040	5.83 ± 2.67	3.693 ± 0.460	2.761 ± 0.055
^{90}Br	1.9 s	1.085 ± 0.148	1.341 ± 0.429	0.81 ± 0.28	1.186 ± 0.180	1.442 ± 0.332
^{90g}Rb	158 s	0.295 ± 0.075	0.028 ± 0.028	10.51 ± 10.85	2.710 ± 0.680	2.779 ± 0.222
^{90m}Rb	258 s	0.359 ± 0.046	0.141 ± 0.141	2.55 ± 2.57	0.688 ± 0.553	0.479 ± 0.153
^{90}Rb		0.654 ± 0.121	0.169 ± 0.144	3.87 ± 3.37		
^{91}Rb	58 s	0.869 ± 0.081	0.675 ± 0.216	1.29 ± 0.43	4.106 ± 0.497	4.027 ± 0.161
^{92}Rb	4.5 s	0.313 ± 0.073	1.475 ± 0.339	0.21 ± 0.07	2.973 ± 0.265	4.154 ± 0.332
^{93}Rb	5.8 s	2.599 ± 0.181	2.615 ± 0.837	0.99 ± 0.33	3.997 ± 0.237	4.095 ± 0.655
^{93}Sr	7.4 m	0.658 ± 0.070	0.545 ± 0.349	1.21 ± 0.78	4.601 ± 0.244	4.909 ± 0.196
^{94}Rb	2.7 s	2.128 ± 0.129	2.537 ± 0.812	0.84 ± 0.27	2.821 ± 0.462	3.243 ± 0.746
^{94}Sr	75.3 s	1.498 ± 0.118	1.510 ± 0.483	0.99 ± 0.33	4.036 ± 0.433	4.576 ± 0.366
^{94}Y	19 m	0.148 ± 0.126	0.034 ± 0.034	4.35 ± 5.72	4.184 ± 0.450	4.610 ± 0.184
^{95}Rb	0.38 s	2.182 ± 0.148	1.596 ± 0.511	1.37 ± 0.45	2.297 ± 0.188	1.713 ± 0.548
^{95}Sr	24 s	2.558 ± 0.207	3.182 ± 0.732	0.80 ± 0.20	4.657 ± 0.269	4.916 ± 0.393
^{95}Y	10 m	0.725 ± 0.587	0.223 ± 0.223	3.24 ± 4.18	5.382 ± 0.646	5.139 ± 0.144
^{96}Rb	0.2 s	0.767 ± 0.072	1.169 ± 0.374	0.66 ± 0.22	0.767 ± 0.072	1.203 ± 0.277
^{96}Sr	1.07 s	2.619 ± 0.181	4.132 ± 0.950	0.63 ± 0.15	3.279 ± 0.191	5.190 ± 0.830
^{96m}Y	0.6 s	0.443 ± 0.031	0.736 ± 0.471	0.60 ± 0.39	0.443 ± 0.031	0.736 ± 0.331
^{97}Sr	0.43 s	2.892 ± 0.194	2.859 ± 0.915	1.01 ± 0.33	2.892 ± 0.194	2.936 ± 0.675
^{97g}Y	3.8 s	0.650 ± 0.193	2.519 ± 0.579	0.26 ± 0.10	1.084 ± 0.611	
^{97m}Y	1.2 s	0.975 ± 0.098	***		3.433 ± 0.291	
^{97}Y		1.625 ± 0.291	2.519 ± 0.579	0.65 ± 0.19	4.517 ± 0.902	5.455 ± 0.218
^{98}Sr	0.65 s	1.852 ± 0.146	2.268 ± 0.726	0.82 ± 0.27	1.852 ± 0.146	2.341 ± 0.539
^{98g}Y	0.55 s	2.832 ± 0.196	1.513 ± 0.484	1.87 ± 0.61	2.832 ± 0.196	3.854 ± 0.617
^{99}Sr	0.27 s	1.157 ± 0.111	0.994 ± 0.636	1.16 ± 0.75	1.157 ± 0.111	0.994 ± 0.447
^{99}Y	1.47 s	2.124 ± 0.190	3.741 ± 1.197	0.57 ± 0.19	3.279 ± 0.220	4.734 ± 1.089
^{99}Zr	2.1 s	1.260 ± 0.131	1.471 ± 0.471	0.86 ± 0.29	4.477 ± 0.253	6.136 ± 0.675
^{99m}Nb	2.6 m	3.657 ± 2.000	0.029 ± 0.029	125.4 ± 142.9	1.612 ± 0.900	1.870 ± 0.206
^{100g}Y	0.74 s	1.330 ± 0.109*	2.926 ± 0.936	0.46 ± 0.15	1.631 ± 0.321	3.231 ± 0.743
^{100}Zr	7.1 s	4.034 ± 0.432	3.300 ± 1.056	1.22 ± 0.41	5.652 ± 1.705	6.504 ± 1.041
^{100g}Nb	1.5 s	1.065 ± 0.190	0.096 ± 0.096	11.07 ± 11.25	6.718 ± 1.715	3.348 ± 0.536
^{100m}Nb	3.0 s	3.264 ± 0.549	0.096 ± 0.096	33.92 ± 34.40	3.264 ± 0.549	3.348 ± 0.53
^{102}Zr	2.9 s	7.833 ± 0.883	4.092 ± 1.309	1.91 ± 0.65	8.355 ± 0.944	4.620 ± 1.063
^{104}Zr	1.2 s	5.017 ± 0.933	2.867 ± 0.917	1.75 ± 0.65	5.017 ± 0.933	1.029 ± 0.463
^{104}Mo	60 s	0.990 ± 1.458	1.081 ± 0.486	0.92 ± 1.41	8.839 ± 1.956	5.020 ± 0.201
^{105}Mo	36 s	3.397 ± 0.279	2.004 ± 0.461	1.70 ± 0.56	5.405 ± 0.673	2.004 ± 0.461
^{134m}Sb	0.8 s	0.981 ± 0.064	2.561 ± 0.820	0.38 ± 0.13	1.163 ± 0.193	2.710 ± 0.623
^{134}Te	42 m	3.038 ± 0.251	3.954 ± 0.632	0.77 ± 0.14	4.199 ± 0.316	6.850 ± 0.192
^{134g}I	52 m	0.540 ± 0.130	0.439 ± 0.048	1.23 ± 0.33	4.739 ± 0.342	7.600 ± 0.456
^{135}Te	19 s	3.344 ± 0.284	4.621 ± 1.479	0.72 ± 0.24	4.197 ± 0.395	5.544 ± 1.275
^{136}Te	17.5 s	2.556 ± 0.189	3.525 ± 1.128	0.73 ± 0.24	2.737 ± 0.262	3.703 ± 0.852
^{136g}I	83 s	0.101 ± 0.171	1.329 ± 0.425	0.08 ± 0.13	2.808 ± 0.311	4.989 ± 0.549
^{136m}I	47 s	0.141 ± 0.013	1.345 ± 0.430	0.10 ± 0.04	0.141 ± 0.013	1.388 ± 0.319
^{136}I		0.242 ± 0.184	2.674 ± 0.605	0.09 ± 0.07	2.949 ± 0.324	6.377 ± 0.868

Nuclide	$T_{½}$	Independent Yield			Cumulative Yield	
		Experimental	ENDF	Expt/ENDF	Experimental	ENDF
^{137}Te	2.5 s	0.960 ± 0.071*	1.568 ± 0.502	0.61 ± 0.20	0.998 ± 0.077	1.568 ± 0.502
^{138}I	6.5 s	1.312 ± 0.172	3.119 ± 0.998	0.42 ± 0.15	1.828 ± 0.372	3.645 ± 0.838
^{140}Cs	64 s	0.945 ± 0.070	0.887 ± 0.204	1.07 ± 0.26	5.770 ± 0.675	5.786 ± 0.116
^{141}Cs	25 s	3.134 ± 0.265	1.913 ± 0.612	1.64 ± 0.54	6.318 ± 0.410	5.109 ± 0.562
^{142}Cs	1.7 s	2.410 ± 0.178	2.280 ± 0.730	1.06 ± 0.35	3.932 ± 0.518	3.850 ± 0.616
^{142}Ba	11 m	0.807 ± 0.081	0.689 ± 0.441	1.17 ± 0.76	4.739 ± 0.525	4.581 ± 0.183
^{143}Cs	1.78 s	3.415 ± 0.267	2.390 ± 0.765	1.43 ± 0.47	3.846 ± 0.269	2.822 ± 0.649
^{143}Ba	14 s	1.200 ± 0.275	1.743 ± 0.401	0.69 ± 0.22	4.984 ± 0.382	4.577 ± 0.275
^{143}La	14 m	1.813 ± 0.377	0.045 ± 0.045	40.47 ± 41.34	6.798 ± 0.536	4.622 ± 0.129
^{144}Cs	1.01 s	1.402 ± 0.103*	1.743 ± 0.558	0.80 ± 0.26	1.525 ± 0.105	1.860 ± 0.428
^{144}Ba	11.5 s	3.433 ± 0.609	2.457 ± 0.565	1.40 ± 0.41	4.909 ± 0.617	4.335 ± 0.477
^{144}La	41 s	0.172 ± 0.276	0.211 ± 0.211	0.81 ± 1.54	4.904 ± 0.657	4.547 ± 0.128
^{145}Cs	0.60 s	0.692 ± 0.075	0.556 ± 0.356	1.25 ± 0.81	0.692 ± 0.075	0.569 ± 0.364
^{145}Ba	4.3 s	3.847 ± 0.404	2.580 ± 0.826	1.49 ± 0.50	4.443 ± 0.409	3.087 ± 0.710
^{145}La	25s	1.387 ± 0.443	0.709 ± 0.461	1.96 ± 1.40	5.830 ± 0.603	3.796 ± 0.228
^{146}Ba	2.2 s	1.564 ± 0.205	1.985 ± 0.635	0.79 ± 0.27	1.666 ± 0.229	2.087 ± 0.480
^{146g}La	6.3 s	1.442 ± 0.131	1.271 ± 0.407	1.13 ± 0.38	3.108 ± 0.264	3.358 ± 0.269
^{146}Ce	14 m	0.310 ± 0.155	0.087 ± 0.087	3.56 ± 3.98	3.418 ± 0.306	3.445 ± 0.096
^{147}Ba	0.89 s	1.321 ± 0.126	0.845 ± 0.549	1.56 ± 1.01	1.321 ± 0.126	0.845 ± 0.380
^{147}La	4.0 s	1.644 ± 0.200	1.481 ± 0.474	1.11 ± 0.38	2.965 ± 0.236	2.326 ± 0.372
^{148}La	1.43 s	0.815 ± 0.061	1.090 ± 0.490	0.75 ± 0.34	1.064 ± 0.256	1.342 ± 0.604

* These values were calculated using branching ratios from Rudstam. [15]

such measurements provide needed input to the evaluated file.

Fig. D1 compares our measured partial chain yields (solid circles) with those from ENDF/B-VI (open squares). Our experimental values have been corrected to account for unmeasured members of the mass chains. For each mass, ENDF/B-VI was used to calculate the percentage of the total chain yield represented by the measured nuclides. The experimental chain yield was then boosted by the missing percentage. For masses between 101 and 105 and between 135 and 138 only a single nuclide was measured in each mass chain and thus the ENDF percentages of missing nuclides have a major effect on the corrected experimental values and their discrepancy with ENDF.

The expected near-Gaussian distribution of elemental yields in our measurements is observed in Fig. D2 for rubidium, strontium, yttrium, cesium, barium, and lanthanum. The solid circles are our experimental values and the open squares are the ENDF values. In most cases the distributions are quite similar although our measured distribution for yttrium indicates a shift to lower mass numbers.

This independent and cumulative yield study of fission product nuclides of ^{238}U is given in full detail in the accompanying thesis of Joann Campbell. This study will soon be written and submitted for publication in Physical Review C .

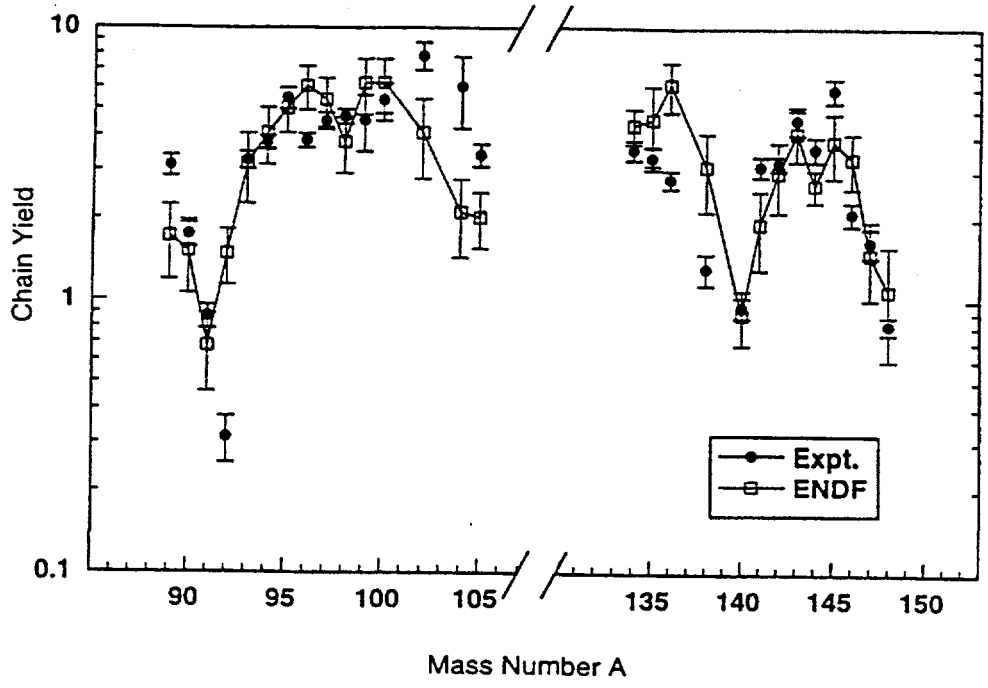

Figure D1. Our ^{239}Pu chain yields corrected for missing nuclides compared with ENDF/B-VI.

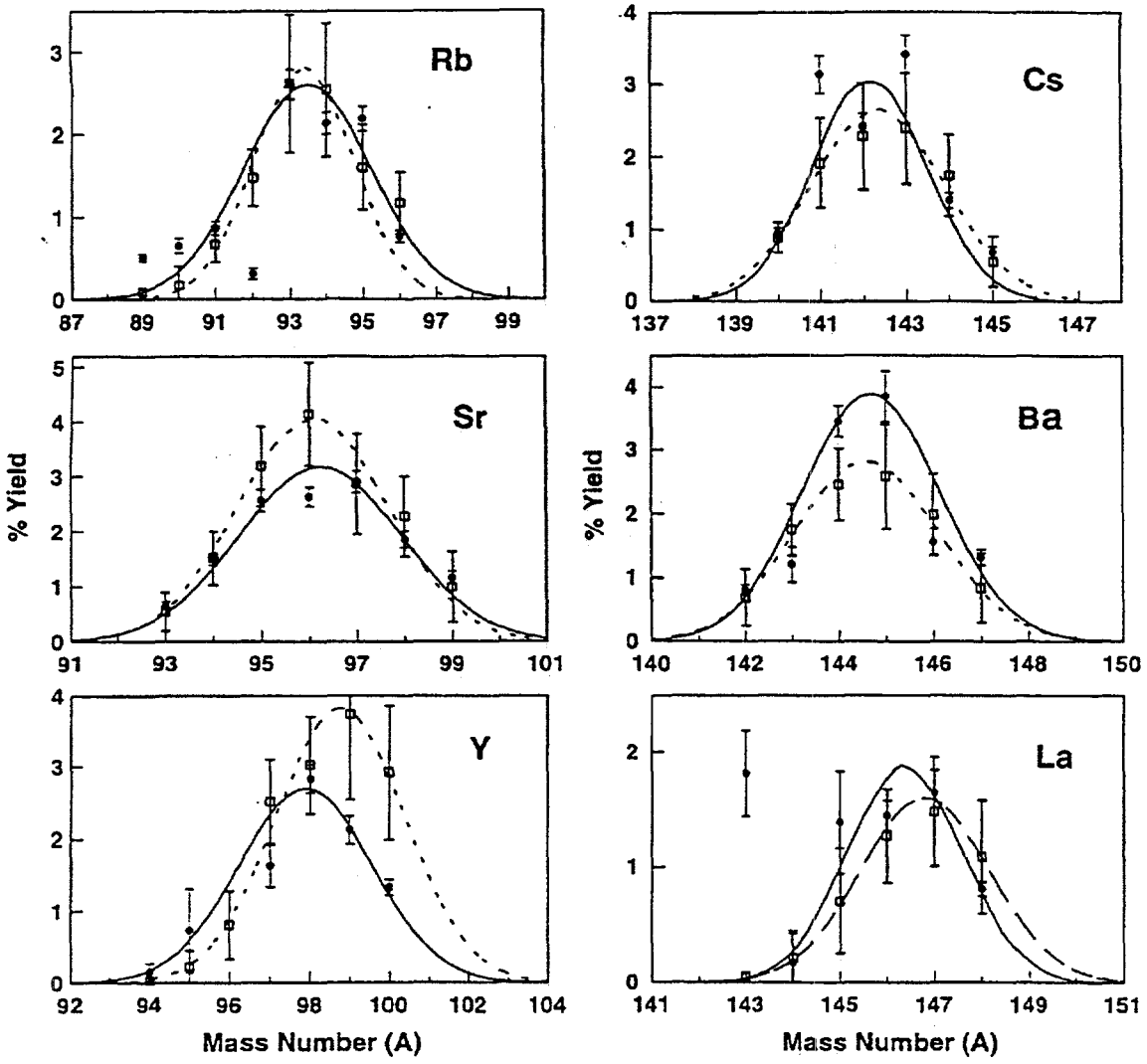

Figure D2. Our ^{239}Pu elemental yield values (solid circles) compared with ENDF/B-VI (open squares).

2. PROJECT RELATED PAPERS

A. JOURNAL PAPERS

1. "Programs in C for Parameterizing Measured 5"x5" NaI Gamma Response Functions and Unfolding of Continuous Gamma Spectra", H.V. Nguyen, J.M. Campbell, G.P. Couchell, S. Li, D.J. Pullen W.A. Schier, E.H. Seabury and S.V. Tipnis, Computer Phys. Comm. **93** (1996) 303.

2. "Relative Efficiency Measurements of Fission Fragment Transfer with a Helium Jet", P.R. Bennett, W.A. Schier, G.P. Couchell, E.S. Jacobs, D.J. Pullen, M.F. Villani, Nucl. Inst. Meth. in Phys. Res. **A369** (1996) 203.

Submitted journal papers:

3. "Beta Particle Spectrometer for Measuring Aggregate Beta Spectra following Fission", W.A. Schier, J.M. Campbell, G.P. Couchell, S. Li, H.V. Nguyen, D.J. Pullen, E.H. Seabury and S.V. Tipnis, Nucl. Inst. Meth. in Phys. Res. **A**

4. "Yields of Short-lived Fission Products Produced following $^{235}U(n_{th},f)$", S.V. Tipnis, J.M. Campbell, G.P. Couchell, S. Li, H.V. Nguyen, D.J. Pullen, W.A. Schier and E. H. Seabury, Phys. Rev.

B. INTERNATIONAL CONFERENCE AND SYMPOSIUM PAPERS

1. "Energy Distributions of Gamma and of Beta Decay Heat as Function of Decay Time for $^{238}U(n,f)$"; W.A. Schier, J.M. Campbell, G.P. Couchell, S. Li, H.V. Nguyen, D.J. Pullen, E.H. Seabury and S.V. Tipnis and T.R. England, Proc. Int. Conf. on Nuclear Data for Science and Tech., May 9-13, 1994, Gatlinburg, TN, Vol. 2, p. 970-973(1994).

2. "A Study of Gamma-Ray and Beta-Particle Decay Heat following Thermal Neutron Induced Fission of ^{235}U"; G.P. Couchell, J.M. Campbell, S. Li, H.V. Nguyen, D.J. Pullen, E.H. Seabury and S.V. Tipnis and T.R. England, Proc. Int. Conf. on Nuclear Data for Science and Tech,, May 9-13, 1994, Gatlinburg, TN, Vol. 2, p. 966-969(1994).

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4. "Cumulative and Independent Fission Product Yield Measurements", W.A. Schier, J.M. Campbell, G.P. Couchell, S. Li, H.V. Nguyen, D.J. Pullen, E.H. Seabury and S.V. Tipnis and T.R. England

Papers that will be presented at Int. Conf on Nuclear Data for Science and Technology, May 19-24, 1997, Trieste, Italy:

5. "A Study of Gamma-ray and Beta-particle Decay Heat following Thermal Neutron Induced Fission of ^{235}U", G.P. Couchell, J.M. Campbell, T.R. England, S. Li, H.V. Nguyen, D.J. Pullen, W.A. Schier, E.H. Seabury and S.V. Tipnis

6. "High-resolution Gamma-ray Spectra for $^{235}U(n_{th},ff)$", D.J. Pullen, J.M. Campbell, G.P. Couchell, T.R. England, S. Li, H.V. Nguyen, W.A. Schier, E. H. Seabury and S.V. Tipnis

7. "Energy Distributions of Gamma and of Beta Decay Heat as Function of Decay Time for $^{238}U(n,f)$", W.A. Schier, J.M. Campbell, G.P. Couchell, T.R. England, S. Li, H.V. Nguyen, D.J. Pullen, E. H. Seabury and S.V. Tipnis

C. PUBLISHED ABSTRACTS

1. "Use of a High Purity Germanium Detector in Aggregate Fission-Product Decay Heat Studies"; D.J. Pullen, J.M. Campbell, G.P. Couchell, H.V. Nguyen, W.A. Schier, S.V. Tipnis and M.F. Villani, Bull. Amer. Phys. Soc. II, **37** (1992) 1279.

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10. "High Resolution Gamma-ray Spectra from Aggregate Fission-Products Measured in $^{235}U(n_{th},f)$"; J.M. Campbell, G.P. Couchell, S. Li, H.V. Nguyen, D.J. Pullen, W.A. Schier and S.V. Tipnis, Bull. Amer. Phys. Soc. II, **38** (1993) 1650.

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3. FACULTY ASSOCIATES AND GRADUATE STUDENTS

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