10
6/14/88 Z/111

(D)

DR 0484-7

UCID--21276

DE88 011357

GAMMA RAY EMISSION FROM SPHERES PULSED WITH D-T
NEUTRONS: RESULTS OF MAY 1987 EXPERIMENTS
AT RTNS-1

E. GOLDBERG
L. F. HANSEN
R. J. HOWERTON
T. T. KOMOTO
B. A. POHL

NOVEMBER 1987

Lawrence
Livermore
National
Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

EB

GAMMA RAY EMISSION FROM SPHERES PULSED WITH D-T NEUTRONS: RESULTS OF MAY 1987 EXPERIMENTS AT RTNS-1

E. Goldberg, L.F. Hansen, R.J. Howerton, T.T. Komoto, and B.A. Pohl

Introduction

Subsequent to the analysis of the June 1986 series of experiments at RTNS -1, we thought it sensible to repeat some of the experiments with greater care given to the high energy portions of the effluent gamma ray spectra. In addition, some new materials were recommended for study, such as silicon. And since among our earlier experiments we observed data which was not highly reproducible, repeated runs would provide a quantitative assessment of the precision of the experiments.

Accordingly, we followed the procedure outlined in UCID-20884.¹ First, we calibrated the NE-213 detector with standard gamma ray sources and checked for linearity of pulse height with energy deposited by electrons. We then conducted experiments at RTNS-1, using spherical configurations of C, Si, Al, H₂O, N₂, Ti, Fe, and C₂F₄. The H₂O was contained in a modified glass flask, while the liquid nitrogen was held in a double-walled steel dewar.

Detector Characteristics

The NE-213 detector used in the present series was the same as that used in the June 1986 series. Briefly, the liquid scintillator was housed in a cylindrical aluminum container capped with a glass window to facilitate attachment to a phototube. The cavity was nominally 2" x 2". Figure 1 illustrates the assembly, with the bubble region configured as it would be if the assembly axis were vertical. For all experiments, the axis was horizontal and passed through the center of the radiation source.

Figure 1. NE-213 detector geometry.

We had the unit which was used in the May 1987 series x-rayed and found the following values (in cm):

$D = 5.39$	$t_g = 0.640$
$L = 5.88$	$t_b = 0.401$
$t_w = 0.165$	$D_B = 4.503$
$t_f = 0.178$	

The cavity volume was calculated to be 101.79 cm^3 and the bubble volume 5.78 cm^3 , leaving 96.01 cm^3 for the scintillator liquid.

Detector Linearity

For this series, we made a greater effort to assess the linearity of the detector. We employed gamma ray sources of ^{22}Na , ^{137}Cs , ^{60}Co , and $^{238}\text{Pu-Be}$, and in addition dealt with sources of ^{228}Th and $^{238}\text{Pu-}^{13}\text{C}$. The latter source generated a 6.13 MeV gamma ray via the $^{13}\text{C}(\alpha, n)^{160}\text{m}$ reaction with no gamma rays of higher energy as in the case of 14 MeV neutron bombardment of H_2O , since the highest energy alpha particles from ^{238}Pu decay were inadequate to excite 160 to levels above 6.13 MeV. Details of the procedure are discussed in detail in UCID-20887.²

We list in Table I the gamma ray sources employed and the corresponding Compton cutoff energies. For the more energetic lines, we also list the energy of the double-escape peak (DEP). We list for each line the channel number corresponding to the Compton edge

or DEP. As discussed in Ref. 1, p.2, we assign the Compton edge to that channel number at which the channel count is 80% of the count at the Compton peak.

Table 1. Channel Number vs. Recoil Electron Energy in NE-213 Detector

Source	h ν (MeV)	E(Electron) (MeV)	Compton Edge	Double Escape Peak	Channel No.
²² Na	0.511	0.341	√		25.5
	1.275	1.061	√		86
¹³⁷ Cs	0.662	0.477	√		37
⁶⁰ Co	1.173	0.963	√		79
	1.332	1.118	√		---
²²⁸ Th	2.615	2.382	√		195
		1.593		√	129
Pu-Be	4.439	4.197	√		350,353
		3.417		√	288,290
Pu- ¹³ C	6.130	5.885	√		474
		5.108		√	416

A good fit to the data is given by the relation:

$$\frac{E(\text{electron}) - 0.033}{0.0120} = \text{channel no.}, \quad (1)$$

where all calculated channel numbers lie within 3% of the results of experiment. (This expression differs from its counterpart in Ref. 1 because we deliberately chose an electronic gain in the present study to enable us to record more energetic pulses due to higher energy gamma rays.)

We also used a light pulser, BNC 6010, which operated at 490 nm, generating 500 ns-wide square wave pulses at a 10 kHz rate to check the linearity of the phototube and associated electronics as a function of pulse amplitude. In order to diffuse

homogeneously the light output from the pulser on the phototube face, the NE-213 scintillator was replaced by a plastic cylinder of equal size, where the optical fiber probe from the pulser was inserted. Excellent linearity was observed for intensities corresponding to the channel interval: 270-975. The upper limit of linearity inferred from the light pulser finding is then 11.7 MeV, if we use the above expression. This finding is qualified, since the pulse width is quite large (i.e., 500 ns vs a few ns for the pulsed sphere experiments).

Detector Calibration

For the present series, we used ^{22}Na , ^{60}Co , and ^{137}Cs calibrated gamma ray sources. We were unable to have access to a ^{24}Na source as in previous instances since the RTNS-II facility where we manufactured ^{24}Na sources previously was in its shutdown phase. The ^{228}Th source, although calibrated, was too weak to be used as a calibration source since it had to be placed within 2 cm of the scintillator face, implying a large geometric uncertainty.

A ^{137}Cs source of 1.05 μCi (3-5-86) was utilized. We find, as illustrated in Fig. 2, that when the SANDYL calculations are smoothed by a function with $\sigma/E = .05$, the calculated shape closely follows experiment, but the calculations exceed experiment by 12%. This is the same discrepancy recorded for ^{137}Cs in References 1 and 2.

For the present series, we initially utilized a newer ^{22}Na source (1.14 μCi , 7-17-85), but found upon comparison of experiment to calculation that the pulse height distributions did not closely match. We then realized that the newer source was in fact one-sixth of the strength of the source that we had used in the June 1986 series (1x743, 8.93 μCi , 4-1-80). We therefore repeated the calibration run with the more intense source. The results are illustrated in Fig. 3. We find a ratio of calculation to experiment to be 1.05 over the 0.511 MeV gamma ray peak and 1.075 over the 1.275 MeV peak. The weaker source gave ratios of 1.08 and 1.13, respectively. Since the background correction was appreciable for the weaker source (20% of the signal in that portion of the recoil electron spectrum midway between the two Compton edges), and the background was seen to be variable ($\pm 12\%$), it is reasonable to discount the results of the weaker source.

A ^{60}Co standard source (0.82 μCi , 1-24-86) was our final calibration source. Fig. 4 compares the experimentally determined recoil electron spectrum to a SANDYL calculation, modified with a smoothing function, $\sigma/E = 0.025$. Further, a conversion relation,

$$\frac{E(\text{electron}) - .033}{.01165} = \text{channel no.} \quad (2)$$

gave a better fit. We see the calculation to exceed experiment by ~9%, a good bit higher than the value found in Ref. 1 (i.e., 4%).

Averaging the above finding, we find for the ratio of the calculated to experimental recoil electron spectrum of:

$$\left(\frac{\bar{C}}{\bar{E}}\right) = 1.09 \pm 0.03 . \quad (3)$$

This is somewhat larger than the value in Ref. 1 of 1.05 ± 0.04 , which was influenced by the value based on ^{24}Na .

Neutron-Induced Gamma Rays

We now turn to the pulsed sphere experiments of May 1987 in which we gave attention to the gamma rays as well as neutrons leaking from the spherical assemblies. The details of the experimental procedure and analysis is given in detail in Ref. 1, pp.10-14. The same geometry was employed. Again the distance between the D-T source and the center of the NE-213 detector was 852 cm. For the present series, the gamma ray time window was 22ns, or one-third the width for the June 1986 series, to further reduce background.

To facilitate the analysis, an edit code, called NUCODE, was written³ to process the gamma ray output spectrum from TART. It generates a table of equal probability energy intervals that is in a format compatible with SANDYL. Further, the gamma spectrum is filtered in exit angle and time, in the same way as the predecessor, XGAMEDIT.

Empirical Assessment of Specific Gamma Ray Output

One convenient way to rank the materials studied as to their gamma ray output is to sum over the electron recoil spectrum in the following way:

$$\sum_i N_i C_i \frac{(C.F.)}{\alpha} \psi \frac{(\text{electron counts} \times \text{MeV})}{\text{alpha particle counts}} \quad (4)$$

Here we sum over the detector channel count (N_i) multiplied by channel number (C_i) to weight by energy, and normalize to the alpha particle count (α). To correct for alterations in channel width, we multiply by the energy conversion factor (C.F.), in MeV/channel. Finally, since we envisage a uniform sphere of material with a (pr) which maximizes the gamma ray output when driven by a central 14 MeV source, we need a correction, ψ , which adjusts the sum to correspond to the optimal (pr). We selected from among the spherical assemblies available to us the ones which would give the largest gamma ray energy release per source neutron for a given material. For the present exercise we used

TART to determine the factor, ψ . The results of the 5/86 and 6/87 series are listed in Table II. Generally, ψ was close to unity.

Of the materials we examined, silicon is the best choice for generation of gamma ray energy fluence, with titanium and aluminum a close second. The value of Eq. 4 for beryllium was 0.43 which is below the value for the blank runs (0.49). This finding is consistent with the behavior of a very weak gamma ray generator, with the material acting to shield the gamma rays originating in the neutron source structure.

Comparison of Experimental Results to TART/SANDYL

A. Blank Runs.

For the May 1987 series, nine blank (i.e., sphere removed) runs were interspersed among the measurements of the different spheres. We selected a typical one, Run No. 10, to compare to TART/SANDYL. The cross section sets in TART were designated TN860206 and PP860209. The data were quite reproducible, with $(\Sigma N_i/\alpha) = 0.503 \pm 5\%$. Following the procedure of Ref. 1, we calculated the recoil electron spectrum for a blank run. Fig. 5 illustrates that result along with the measured spectrum.

To assess the degree of agreement, let us first identify from TART the gamma ray sources (per source neutron). The photon source edit shows a total of 0.27 MeV of gamma rays generated per source neutron. The tungsten target backing accounts for 26%, the remaining neutron source structure accounts for 28% and the remaining 46% arises in the air. However, those gamma rays generated in the air, except for a very small fraction, cannot pass through the collimator. Accordingly, the gamma ray signal seen by the NE-213 detector is equivalent to a gamma ray output from the blank configuration of 0.15 MeV gamma rays/source neutron. To place this in perspective, we observe that TART calculations show that a silicon sphere releases 2.15 MeV gamma rays per central source neutron ($E_N = 14$ MeV). We may further note that the findings for tungsten in Ref. 1 gave a ~30% underestimate of gamma ray energy fluence, so an adjustment of calculation to experiment would drop the tungsten contribution from 0.07 to 0.05 gamma ray MeV/neutron. The correction, in the case of silicon, would be a mere 1%. Since the largest correction for the blank run arises from modelling of tungsten, an upward adjustment of the calculated electron recoil spectrum of ~0.02/0.15, or 13% is warranted. If applied to Fig. 5, we would see closer agreement between experiment and calculation. From such reasoning, we conclude that the uncertainty in modelling the low mass neutron source is equivalent to ± 0.03 gamma ray MeV/source neutron, reflecting in part the need to improve the cross section database for relevant materials (e.g., W, Fe, Al). For experiments with spheres in place, the spheres act to shield the source assembly, so generally the uncertainty associated with modelling of the source is mitigated.

We may recall that experiments were performed earlier with a copper shadow bar to assess the role of air scattering and background due to neutron and gamma ray production in the deuteron beam transport system (Ref. 1, pp.16-17). There we saw the shadow-shielded signal to be ~7% of the blank run signal which amounts to $(0.15 \times .07)$, or 0.01 MeV of gamma rays per source neutron. We may conclude that background of unknown origin is very small and well within experimental uncertainty when compared to the output of the assemblies listed in Table II, except for the beryllium run.

Table II. Specific Gamma Ray Energy Fluence, $\frac{\sum_i C_i N_i \psi(C.F.)}{\alpha}$, for Different Materials Investigated.

Material	Radius (cm)	$\rho \Delta R^*$ (gm/cm ²)	ψ^+	$\frac{\sum_i C_i N_i \psi(C.F.)}{\alpha}$ (arbitrary units)
graphite	10.16	17.7	1.42	3.02
				3.19
iron	4.46	31.3	1.02	3.51
				3.88
water	14.48 (H ₂ O)	13.4 (H ₂ O)	1.12	2.49
		+1.1 (SiO ₂)		2.43
lead	5.60	59.4	1.09	0.84
				0.95
gold	6.21	11.9	1.06	1.06
tungsten	10.36 (shell)	49.0	1.04	1.33
tantalum	16.6	51.1	1.00	1.67
copper	4.00	32.94	1.07	2.55
²³² Th	5.76	61.8	1.07	1.07
²³⁸ U	3.63	55.8	1.01	1.14
aluminum	8.94	22.4	1.12	4.65
				5.15
silicon	10.16	21.1	1.11	5.58
nitrogen	19.05 (N)	14.76 (N)	1.24	4.11
		+2.31 (steel)		
titanium	8.94	37.7	1.02	4.89
teflon (C ₂ F ₄)	16.5	35.2	1.00	1.98
beryllium	12.6 (shell)	8.47	--	0.43 ψ
blank	--	--	--	0.50 ψ

* calculated along source-detector axis of symmetry.

+ see text

B. Tungsten Revisited.

In Ref. 1, we saw that the recoil electron spectrum calculated from TART/SANDYL was 30-40% below the June 1986 RTNS-1 experimental finding for tungsten. We reviewed the literature and found information that had not been available at the time of the initial tungsten cross section evaluation. Also an ENDF/B-5 neutron-induced photon cross section set existed which had not been tested.

A useful measure of gamma ray energy production is:

$$\sum \sigma_i \times E_i (\text{gamma}) (\text{barn-MeV}) , \quad (5)$$

that is, energy-weighted gamma ray production cross section. We list values of Eq. 5 from various sources in Table III, for $E_N = 14$ MeV.

Table III. Values of $\overline{\sigma E}$ (gamma) for Tungsten from Various Sources for 14-MeV Neutrons.

Source	$\overline{\sigma E}(\text{b-MeV})$	Comments
1. ENDL PP840818	8.69	Livermore, used in Ref. 1
2. ENDL TG870815	9.90	Livermore revised ⁴
3. ORNL-4847	9.95	Experimental data ⁵
4. TGEF 8707	7.57	ENDF/B-5 File ⁶
5. Bezotosnyi	15.98	Experimental data ⁷

Table III has a considerable spread among the measurements and evaluations, with ENDF/B-5 the lowest and the Soviet experimental work the highest, differing by a factor of two.

Fig. 6 compares the experimental pulsed sphere data first reported in Ref. 1 to recoil electron spectra based on Sets 1, 2, and 4 of Table I. Recalling that tungsten had been underestimated by calculations earlier (i.e., set 1), we see that the ENDF/B-5 set is worse yet by 10-15%. On the other hand, the revised ENDL Set 2 is an improvement over set 1, but a 20% discrepancy still remains. The calculation based on Set 2 utilizes the current default set at LLNL when TART is employed.

C. Iron

As part of the May 1987 series, we repeated the iron experiment, using the 4.46 cm-radius sphere. Fig. 7 compares the experimental recoil electron spectrum to the TART/SANDYL results. If we sum each spectrum weighted by channel number (which is approximately equivalent to energy), we find, for the average ratio of calculated to experimental recoil electron spectrum $\overline{(C/E)}$:

$$\overline{\left(\frac{C}{E}\right)} = \frac{\sum_i \left(\frac{C}{E}\right)_i N_i C_i}{\sum_i N_i C_i} = 1.00 \quad (6)$$

This is somewhat surprising since we found for iron in Ref. 1 an unweighted (C/E) ratio of 1.2. We now infer an energy-weighted average, over three runs, of

$$\left(\frac{C}{E}\right)_{av.} = 1.10 \pm 0.09. \quad (7)$$

The uncertainty quoted relates to the reproducibility of the experiments. This ratio is useful when applied to a simple TART result. For a uniform sphere of iron with a 14 MeV neutron source at its center, and $pr \sim 40 \text{ g/cm}^2$ to maximize the gamma ray energy leakage, TART calculations give 1.49 gamma ray MeV per source. We infer therefore from the above findings that experiment should give 1.36 gamma ray MeV leaked per 14-MeV neutron for iron.

D. Nitrogen.

When 14-MeV neutrons are transported through air, the spectrum is degraded and modified in a complex way, and gamma rays are generated. To better understand the dosimetric aspects of the process, experiments utilizing nitrogen were performed at LLNL several years ago.^{8,9} Although agreement was good, we thought it prudent to repeat one of the experiments, preferably with the configuration which most nearly maximized the gamma ray energy leakage. Accordingly, we used the liquid nitrogen spherical dewar flask, illustrated in Fig. 8. (See Ref. 8, p.121.)

Due to incomplete documentation on the geometry of the dewar, dimensions were remeasured via x-ray photography at LLNL by R.D. Rickard. In Fig. 8, the liquid nitrogen thickness along the axis of symmetry of the low mass target assembly is 18.3 cm, while the x-ray photo gave 17.9 cm, only 2% less. Along the same axis, the cumulative thickness of stainless steel is 0.29 cm from both Fig. 8 and the x-ray photo. Simple one-dimensional TART calculations examining the relationship of (gamma ray energy leakage vs pr) indicated that for a liquid nitrogen-filled dewar, the 2% discrepancy in $(pr)_N$

correlates with a 1% increase in gamma ray energy leakage, for a nitrogen sphere with $\rho r \sim 0.808 \times 18.3 \text{ g/cm}^2$. Consequently, we did not rerun TART/SANDYL, but rather take note of the 1% systematic error, if the x-ray measurements are accepted as more accurate than the dimensions of Fig. 8.

Data were taken for the empty and filled dewar. TART calculations show that for the empty dewar, 0.26 MeV of gamma rays per neutron are generated in the steel walls of the dewar, 0.11 MeV of which is attributed to the outer shell. Overall, 0.48 gamma MeV per neutron are generated, 0.11 of which is due to air. When filled with liquid nitrogen, TART assigns 1.19 MeV of gamma rays to the nitrogen, and steel-generated gamma rays are reduced somewhat due to shielding, to 0.23 gamma MeV per neutron. The air and tungsten backing each contributes 0.07 MeV.

Fig. 9 illustrates the comparison of experiment to TART/SANDYL for the empty dewar. We see excellent agreement over most of the channel range. For electrons in the detector below 1.0 MeV and above 4 MeV, calculation falls below experiment by $\sim 20\%$. Since the TART database utilized the earlier tungsten cross section (i.e., TN870108 and TG870514) the discrepancy is likely due in part to the modelling deficiency for tungsten.

Fig. 10 illustrates the experimental recoil electron spectrum (RES) for the liquid nitrogen-filled dewar and the TART/SANDYL comparison. Generally the agreement is excellent, and $\langle \bar{C}/\bar{E} \rangle$ (calculated RES/experimental RES) is found to be 0.99.

A series of simple one-dimensional TART calculations shows that for a nitrogen sphere with $\rho r (^{14}\text{N}) \sim 30 \text{ g/cm}^2$, 1.35 gamma ray MeV per 14 MeV neutron leaks from the sphere. Using $\langle \bar{C}/\bar{E} \rangle$ from the preceding discussion, we find a maximum conversion to leakage gamma rays of 1.36 gamma ray MeV per central source neutron, experimentally based.

E. Graphite

The 10.16 cm-radius graphite spherical assembly with a density of 1.76 gm/cc was employed in the May 1987 series as well as the June 1986 series. The earlier results were documented in Ref. 1. Fig. 11 illustrates the results of the May 1987 experiment and the TART/SANDYL results. The SANDYL results were smoothed to account for the detector resolution. Also, the conversion factor was reduced from 0.012 to 0.0115 MeV per channel to match the calculated position of the Compton cutoff for the 4.43 MeV gamma ray with experiment. The present measurement gives a ratio, $\langle \bar{C}/\bar{E} \rangle$, of 0.86 for the more recent run and 0.94 for the 1986 run, yielding an average of:

$$\langle \bar{C}/\bar{E} \rangle = 0.90 \pm 0.04 \quad (8)$$

The quoted uncertainty relates to the reproducibility of the experiment.

In the TART calculation, the total gamma ray source generated per source neutron is 1.00 MeV, of which 0.785 MeV is made in graphite. The air generates 0.088 MeV of gamma rays. To gain additional perspective as we did for ^{14}N , let us estimate, based on the experimental findings, the maximum gamma ray energy which would leak, per 14-MeV neutron, from a graphite sphere whose source is at the center. From simple TART calculations varying over ρr , we find a maximum of 0.90 gamma ray MeV leaking per source neutron, ~50% of it 4.439 MeV. The above $(\bar{\sigma})$ ratio, when applied, leads to a finding, based on experiment, of 1.00 gamma ray MeV per 14 MeV neutron.

We observe in TART that the cross section for generating 4.439 MeV gamma rays for 14 MeV neutrons is 230 mb, which gives $\sigma E = 1.02$ barn-MeV. If we increased the cross section to 256 mb, the ratio, $(\bar{\sigma})$, would move close to unity. This latter cross section agrees with that of Bezotosnyi,⁷ but generally the inelastic scattering cross section for excitation of the 4.439 MeV level in ^{12}C is reported at 230 mb.^{10,11}

F. Silicon.

A spherical assembly of polycrystalline silicon was specially fabricated for the May 1987 series, with density at the theoretical value, 2.33 g/cm³. Fig. 12 illustrates the geometry. TART/SANDYL results are compared in Fig. 13 to the recoil electron spectrum we measured. We see that the general features match, but calculation exceed experiment for electron energies below 4 MeV and fall below experiment above 4 MeV. The energy-weighted ratio is found to be :

$$(\overline{C/E}) = 1.11. \quad (9)$$

Several authors have reported microscopic cross section measurements upon silicon with varied results.^{7,10,12,13} As we did in the case of tungsten, a simple measure of gamma energy production is given by Eq. 5. Let us compare the various results with the current ENDL set, employed in the TART (ENDL) database.

Table IV. Values of $(\overline{\sigma E \gamma})$ for Silicon

Source	(Barn-MeV)	Reference
ENDL	7.3	TG870815
Bezotosnyi	7.2	7
Drake	4.5	10
Dickens	4.7	12
Rogers	4.3	13

Now, the silicon assembly has a $[p(\text{silicon}) \cdot \Delta r] = 21.1 \text{ g/cm}^2$, so the source neutron spectrum is not significantly softened.¹⁴ We may then crudely estimate from the pulsed sphere comparison to TART a value for the above integral:

$$7.3 \times (1.11)^{-1} = 6.6 \text{ barn-MeV} \quad (10)$$

This is 27% above the average of the four independent experimental results.

Finally, we calculate with TART 2.15 gamma ray MeV per 14 MeV neutron as a maximum leakage value (at $\sim 35 \text{ gm/cm}^2$). When the $(\bar{C}/E)$ value is applied, we find the experimentally-based leakage of 1.95 gamma ray MeV per neutron, which is twice the value assigned to carbon.

G. Titanium

Titanium was also studied. For this, we employed a metal spherical assembly of 8.94 cm-radius, with dimensions taken from Ref. 8, p.183. Fig. 14 compares the measured recoil electron spectrum to calculation which utilized TART and SANDYL. We see for $E(\text{electron}) < 1.5 \text{ MeV}$ that calculation falls visibly below experiment and for most of the rest there is good agreement. We find the energy-weighted ratio to be:

$$(\bar{C}/E) = 0.87. \quad (11)$$

Let us compare, as we did with silicon, the energy-weighted gamma ray production cross section in units of barn-MeV. We list the findings in Table V.

Table V. Values of $(\bar{\sigma E \gamma})$ for Titanium

Source	$\sum_i \sigma_i E_i$ (Barn-MeV)	Reference
ENDL	6.6	TG870815
Bezotosnyi	10.5	7
Drake	6.7	10
Morgan	8.4	15

The ENDL set agrees closely with Drake,¹⁰ but the spread among experimenters is considerable. Since we find $(\bar{C}/E) = 0.87$, a value of $(6.66/0.87)$, or 7.6 barn-MeV would be suggested by our measurements. Since the thickness to neutrons of the titanium is ~ 38

gm/cm², and since the removal cross section for 14 MeV neutrons traversing titanium is 0.0166 cm²/gm,¹⁴ we have 0.63 mfp, indicating an attenuation factor for 14 MeV neutrons of 0.53. We cannot therefore claim to have measured a microscopic cross section, but do see the titanium experiment to be very sensitive to the choice of energy-weighted gamma ray production cross section.

A simple TART series shows that in the range of 45 gm/cm² of titanium, the gamma ray leakage energy per centrally-generated 14 MeV neutron peaks and is 1.44 gamma ray energy per neutron. Since we found $\langle \frac{\bar{E}}{E} \rangle = 0.87$, the experimentally-based leakage rises to 1.66 MeV of gamma ray energy per source neutron, ~15% below the silicon results.

H. Aluminum

In Ref. 1, we reported that the recoil electron spectrum due to an aluminum sphere exhibited evidence of a moderately high gamma ray energy tail. Having given greater care to characterize the NE-213 detector for the May 1987 series, we repeated the aluminum experiment, using the 8.94 cm-radius assembly. (See Ref. 8, p.161.) We compare the result of the May 1987 experiment to the TART/SANDYL result in Fig. 15. Agreement is fairly good, even better than for the 1986 run. We find the energy-weighted ratio of the recoil electron spectrum of calculation to experiment to be:

	$\langle \frac{\bar{E}}{E} \rangle$
Run 38, June 1986	1.139
Run 9, May 1987	1.058
Average	1.10 ± 0.04

Now let us review the cross section status. Again, we focus on measurements from which we can extract (barn-MeV) of gamma rays for 14 MeV neutrons. We also list in Table VI the value from the ENDL base which is utilized in TART.

Table VI. Values of $\langle \sigma E \gamma \rangle$ for Aluminum

Source	$\sum_i \sigma_i E_i$ (Barn-MeV)	Reference
ENDL	6.3	TG870815
Bezotosnyi	5.7	7
Drake	4.1	10
Dickens	4.3	16

Using the average ratio of $\left(\frac{\bar{\sigma}}{\bar{\sigma}_E}\right)$, we suggest, based on our experiments, a value of 6.3/1.10, or 5.7 barn-MeV. It appears from Table VI and our finding that the ENDL data overestimates gamma ray production for aluminum.

Finally, we observe that for an aluminum sphere with a central 14 MeV-neutron source whose radius is chosen to maximize gamma ray energy leakage (i.e., $\rho \Delta r \sim 35 \text{ gm/cm}^2$) TART yields 1.97 gamma ray MeV per 14 MeV neutron. If we apply the value of $\left(\frac{\bar{\sigma}}{\bar{\sigma}_E}\right)$ found above, we find the experimentally-based leakage value to be 1.79 gamma ray MeV per 14 MeV neutron, 9% below silicon.

I. Teflon

To study fluorine, we employed a teflon spherical assembly of 16.5 cm-radius. The chemical composition, C_2F_4 , ensured a high fluorine content. The geometric details are given in Ref 8, p.293. Our initial comparison of calculated to experimental recoil electron spectra, shown in Fig. 16, revealed a striking discrepancy, as large as a factor of four!

One reason that the fluorine cross section evaluation had not been updated in the last 15 years is that the pulsed sphere experiments which generated neutron time-of-flight spectra were in accord with TART calculations, as seen in Fig. 17. On closer study, it has become clear that the cross section database which underlies gamma ray production does not agree with microscopic cross section measurements. We find from the ENDL base for 14-MeV neutrons a value of $(\bar{\sigma}_E\gamma) = 6.2 \text{ barn-MeV}$ (PPD61110, 10-11-86), while experiments at ORNL gave for neutrons in the 12-14 MeV energy range a value of $(\bar{\sigma}_E\gamma) \sim 0.86 \text{ barn-MeV}$.¹⁷ Earlier Soviet work gave a smaller value, 0.63 barn-MeV as a sum over five distinct lines.¹⁸

Accordingly, a reevaluation of the nuclear cross sections for fluorine was undertaken. Incorporated in this was the recent finding that at $E_N = 14.8 \text{ MeV}$, the ^4He production cross section is $501 \pm 36 \text{ mb}$,¹⁹ which is much larger than the earlier ENDL-derived value of 75 mb. The new cross section set, at $E_N = 14.0 \text{ MeV}$, includes the values (TL870815):

$$\sigma(n,n'\alpha) = 0.474 \text{ barns}$$

$$\sigma(n,\alpha) = 0.025 \text{ barns}$$

In the present model the ^4He from the $(n,n'\alpha)$ reaction carries off much of the energy previously allocated to gamma rays. The new file, TG870815, utilized when gamma rays are explicitly tracked, shows an appreciable drop to $(\bar{\sigma}_E\gamma) = 1.80 \text{ barn-MeV}$.

Fig. 16 illustrates the effect of the cross section reevaluation. The calculated recoil electron spectrum still lies above the experimental counterpart, with the calculation only 30-40 percent above experiment. Note, however, that teflon is C_2F_4 , and we found for graphite a ratio, $(\bar{C}/E) = .90$, so we may anticipate for fluorine a lower value still of $(\bar{\sigma}E\gamma)$. A crude argument points to a value of $(\bar{\sigma}E\gamma)$ of 1.2 barn-MeV at $E_N = 14$ MeV for fluorine to reconcile with our experiment.

J. Water

We saw in the previous series of June 1986 that the gamma ray spectrum leaking from the water-filled vessel was rich in high energy photons.^{1,20} This prompted us to repeat the water experiment in the May 1987 series. In the interim period, we employed a number of different cross section sets, including ENDF/B-5.²⁰ For the latter, the TART/SANDYL results fell considerably below the experimental recoil electron spectrum.

Subsequent to the release of the study of the H_2O -filled assembly,²⁰ one additional adjustment was made in the 160 set, to account better for the 6.05 MeV level in 160 when decaying by internal conversion. (Recall that this level is 0^+ , as is the ground state.) TART and SANDYL calculations were run with the amended set (TL870815 and TG870815) and the results are illustrated in Fig. 18. Comparison is made to the results of experiment of May 1987. In the mid-range of investigation, agreement is excellent. Solving for $(\bar{C}/E)$, Eq. 6, we find $(\bar{C}/E) = 1.10$. Results of June 1986 gives $(\bar{C}/E) = 1.18$. We extract then an average of:

$$(\bar{C}/E) = 1.14 \pm 0.04 . \quad (12)$$

Following the arguments outlined above, we find, for a sphere of 160 whose radius is chosen to maximize gamma ray energy leakage, an experimentally-based leakage value of 1.40 gamma ray MeV per 14 MeV neutron.

Table VII summarizes the Values of $(\overline{\sigma E\gamma})$ for ^{160}Gd at $E_N = 14$ MeV from various sources. The value most compatible with the experimental data from this study is 3.07/1.14, or 2.69 barn-MeV. This is quite compatible with the ORNL finding.

Table VII. Values of $(\overline{\sigma E\gamma})$ for ^{160}Gd .

Source	$(\overline{\sigma E\gamma})$ barn-MeV	Reference
ENDL	3.42	PP840815
ENDL	3.07	TG870815
ORNL	2.51	21
Yamamoto	1.07	22
Orphan	1.50	23
Engesser	2.67	24

Uncertainty Analysis

In the present study, we have compared experimentally determined pulse-height distributions to their calculational counterpart. We ask now what uncertainties are to be attached to our findings. One specific task should be assessment of the uncertainty to be attached to the ratio of counts in a particular channel:

$$\frac{n_i(\text{calc.})}{n_i(\text{exp.})} \quad (12)$$

Our convention has been to let the experimentally determined counts per channel, $n_i(\text{exp.})$, remain unaltered, and derive $n_i(\text{calc.})$ following the method of UCID-20884.* Many of the factors which contribute to the overall uncertainty are immediately identified

* See Ref. 1, p.14. The correct expression for the June 1986 series is:

$$n_i \left(\frac{\text{cts}}{\text{channel}} \right)_{\text{calc.}} = \left(\frac{\text{cts}}{\text{MeV photon}} \right)^{\text{SANDYL}} \times A_D \times 1.29 \cdot 10^7 \times \left(\frac{\text{PRCB}}{\alpha} \right)_{\text{Blank}} \times \alpha_j \times \frac{4\pi}{1.06} \\ \times \left(\frac{\text{tallied photons}}{\text{neutron}} \right)_{\text{TART}} \times \frac{1}{.06699 \times 4\pi(\Delta Z)^2} \times \text{CF} \left(\frac{\text{channels}}{\text{MeV}} \right) \times \frac{1}{1.05}$$

such as the neutron source strength, through the segment: $1.29 \times 10^7 (\text{PRCB}/\alpha)_{\text{Blank}} \times \alpha_j$ where α_j is the alpha particle count for Experiment j. Here we have to estimate the systematic and statistical uncertainties.

As a starting strategy, let us consider a specific configuration, the iron sphere of 4.46-cm radius, and list the many sources of statistical and systematic uncertainties. This exercise will concentrate on the uncertainties associated with neutron-induced gamma rays.

1. Room Background

Our shadow shield experiment¹ showed the recoil electron spectrum (RES) to be 7% of the RES from a blank run. Repeating an earlier argument, our TART calculations of a blank run gave $\sim 0.15 \gamma$ MeV per 14-MeV neutron, so we assign 0.01γ MeV per source neutron which likely arises in the beam transport pipes upstream of the neutron source which is visible to the NE-213 detector. In our earlier discussion of an iron sphere, we found a gamma ray output of 1.3 MeV, so we conclude that the beam transport system may contribute $0.01/1.3$, or $\sim 0.7\%$ to the signal.

The air in the experiment is modeled approximately. Now $\rho Z \sim 1.1 \text{ gm/cm}^2$ from source to detector which attenuates gamma rays by $\sim 3\%$. Furthermore, our model incorporates an edit procedure to filter out gamma rays impinging on the escape surface at an angle which implies entry into the collimator at an angle larger than that which is allowed by the collimator diameter and position of the detector. We judge the uncertainty to be 1%.

Another subtle background effect involves electrons generated by gamma rays in the air and collimator surfaces. To assess this effect, the geometry had to be simplified in SANDYL calculations, to avoid consumption of many hours of CRAY time. We found that signals due to direct impact of electrons on the detector assembly contributed $\leq 1\%$ of that due to gamma rays. Most of the (weak) direct electron signal arose from gamma rays which struck the inner surface of the collimator.

2. Neutron Source Calibration

As discussed in UCID-20884, we employed a calibrated proton-recoil counter (PRC). Its accuracy, as we employed it, was $\pm 6\%$. In a typical run, the PRC recorded $> 10^5$ counts. The statistical uncertainty is then $< 1\%$.

3. Neutron Source Angular Distribution

We estimate the uncertainty to be $\pm 1\%$ from prior investigation.²⁵

4. Iron Sphere Characteristics

We estimate the uncertainty in pr to be $\sim 1\%$. Since we chose the pr to maximize the leakage gamma rays, the effect on leakage gamma ray flux of this slight change in pr is negligible (see Ref. 20, Fig. 3 as illustration).

5. Placement of Neutron Source Target

Special TART calculations showed that if we were able to position the spherical assembly with respect to the low mass neutron source with an accuracy of ± 0.1 cm, the gamma ray energy fence would vary by $\pm 2\%$. Our estimated placement accuracy was ± 0.1 cm.

6. Location of NE-213 Detector

The spacing between neutron source and detector center was 852.5 cm with an uncertainty of < 1 cm. Therefore, this effect contributes $\sim 0.2\%$ to the overall uncertainty.

7. NE-213 Detector Model, Calibration

The NE-213 detector was x-rayed to check its dimensions against the manufacturer's documentation. Important discrepancies were found. We chose to model the gas bubble, which occupied $\sim 6\%$ of the enclosed cylindrical space, as an annulus rather than a distorted bubble in the upper portion of the enclosed space to simplify the calculation. The annulus degraded the energy deposited by electrons by $\sim 7\%$. These details were rendered irrelevant by the calibration program which involved exposure to calibrated gamma ray sources. Recalling a correction factor of 1.05 for the June 1986 series and 1.09 for the May 1987 series, we estimate conservatively the statistical uncertainty assigned to the detector to be $\pm 4\%$. Since we do not understand the cause of the detector correction factor, a systematic uncertainty of $\pm 5\%$ is assigned.

8. Reproducibility of Experiments

Common to both experimental series were the spherical assemblies of graphite, aluminum, water, and iron. The average ratio of $\left(\frac{\bar{E}}{E_0}\right)$ is 0.943 ± 0.054 , which should be increased by 0.04 to account for the difference in the NE-213 correction factor between the two series. More relevant is the uncertainty, $\pm 5.4\%$, a statistical contribution. In our earlier discussion of iron (Section C.), an

uncertainty of $\pm 9\%$ due to non-reproducibility (the worst example) was noted. In the compilation below, we will list the average non-reproducibility contribution.

9. Conversion Factor

One step in the analysis to transform the SANDYL output to the observable, (counts/channels), involves the conversion factor, (channels/MeV). We observed, in the case of the ^{12}C sphere and C_2F_4 assembly, evidence of instability of the electronics that suggested an uncertainty in the conversion factor of $\pm 4\%$.

10. Pulse-Shape Discrimination

The pulses generated in the NE-213 detector are processed so that those due to neutrons are counted separately from those due to gamma rays. The analyzer display showed ample separation of the two groups, so that errors due to mistaken identification are negligible. The pulse height distribution associated with the pulse shape discrimination circuit is shown in Fig. 1 of Ref. 20.

11. Gamma Ray Time Cutoff and Background Correction

In the second series, the time window for gamma ray acceptance was 22 ns. We found the window loss to be $< 0.5\%$. Even in the largest spherical assemblies used in the present study, the 14-MeV neutron transit time is ~ 3 ns. The continuous gamma ray background correction was estimated to be $< 1\%$.

12. Statistics on TART and SANDYL

Generally in the TART calculations, $\sim 10^6$ neutrons were generated, and $> 10^4$ gamma rays were tallied across a spherical surface with a 30° half-angle. For SANDYL, generally 4×10^5 gamma rays were followed, with $\sim 10^5$ interacting in the NE-213 detector. Since we utilized 100 bins to sort the electron deposition energy, the average population per bin was 10^3 counts. For higher electron energies, the statistics were quite severe. Where the gamma ray spectrum exhibited a smooth exponential falloff with energy, we averaged over a number of adjacent bins to improve statistics, striving to achieve a statistical uncertainty $< 10\%$.

Table VIII summarizes our findings. If we add all the uncertainties in quadrature, we find an overall uncertainty of $\pm 11\%$, not including the statistical contributions associated with the actual experimental data points or TART/SANDYL statistics.

Table VIII.

Sources of Uncertainty In $\frac{\text{Calculated Recoil Electron Spectrum}}{\text{Experimental Recoil Electron Spectrum}}$ for Fe Sphere

No.	Item	Systematic	Statistical
1.	Room Background	1%	
2.	Neutron Source Calibration	6%	1%
3.	Neutron Source Ang. Dist.	1%	
4.	Sphere Characterization	< 1%	
5.	Source Target Position	2%	
6.	NE-213 Detector Position	< 1%	
7.	Bubble Model, NE-213 Calib.		4%
8.	Reproducibility of Experiments		5%
9.	Conversion Factor	4%	
10.	Pulse-Shape Discrimination	< 1%	
11.	X-ray time Window	< 1%	
12.	TART/SANDYL Stat.		<10%
NET (Not including #12)		11.4%	

13. Miscellaneous Errors in Code Model

We have considered some possible sources of error above such as density and dimensions of sphere, placement of source target and modeling of the bubble in the NE-213 scintillator. We now arbitrarily attribute to the neutron cross section set in TART the blame for any discrepancy between the calculated and experimental recoil electron spectrum (RES). More will be said below in the discussion. We choose to display these statistical components explicitly on the preceding illustrations.

If our models accurately portray the experimental details, we suggest that discrepancies between experimental and calculated spectra are due to shortcomings in the neutron cross section database. When such discrepancies exist, a defensible response is one which turns our attention to the database. An updating of the

database may be in order. We do not allow ourselves the option of adjusting selectively the cross sections to bring experiment and calculation into agreement.

Discussion and Summary

Initial analysis of the June 1986 and May 1987 series of experiments at RTNS-1 has been completed. Comparisons of the gamma-ray-induced recoil electron spectra to TART/SANDYL-based calculations with ENDL cross sections has revealed many discrepancies which warranted review and revision of some of the database sets. In isolated cases, we employed ENDF/B-5 cross sections and found discrepancies with experiment.

We summarize the findings of the average ratio of calculated recoil electron spectrum for a given material to the experimental counterpart for those materials studied in the May 1987 series in Table IX.

Table IX. Summary of Comparison of Calculated to Experimental Recoil Electron Spectra

Material	$\overline{(C/E)}$	Comments
Iron	1.10	ENDL (1984)
Nitrogen	0.99	ENDL (1984)
Silicon	1.11	ENDL (1984)
Titanium	0.87	ENDL (1984)
Aluminum	1.10	Average of 6-86 and 5-87 Runs
Teflon (C ₂ F ₄)	~4	ENDL (1984)
	~1.5	ENDL (1987)
Water	~1.4	ENDL (1984)
	1.14	ENDL (1987) (Average of 6-86 and 5-87 Runs)

An uncertainty analysis was undertaken. For a typical material, the overall uncertainty, not including the statistical contribution from TART, SANDYL, and NE-213 counts due to gamma rays, is $\pm 11\%$. Meaningful comparisons of the calculated recoil electron spectra to their experimental counterparts easily may be made out to the channel range where the statistical uncertainties for calculation and experiment is $\pm 10\%$ each. We are inclined to interpret discrepancies between calculation and experiment as evidence of shortcomings in the nuclear cross section database employed in the calculations.

Some insight into the degree of scatter of the $\bar{\sigma}_0$ values was gained through examination of the literature which documented microscopic cross section measurements for the materials we studied. Immediately apparent was the general paucity of data on nuclear processes which generated neutron-induced gamma rays. Further, where independent experimental studies were performed, often discrepancies were recorded, many well in excess of the quoted uncertainties.

References

1. UCID-20884, "HOTSPUR: Gamma Ray Emission from Spheres Pulsed with D-T Neutrons, I. Calibration..., II. Experiments..., " E. Goldberg, L.F. Hansen, T.T. Komoto, B.A. Pohl (Sept. 1986).
2. UCID-20887, "HOTSPUR: Neutron Induced Gamma Rays Emitted by D-T Neutron Pulsed Sphere--Detector Calibration," E. Goldberg, L.F. Hansen, and B.A. Pohl (Feb. 28, 1986).
3. E.F. Plechaty, private communication.
4. Private communication, R.J. Howerton and H.M. Blann; set of August 15, 1987.
5. J.K. Dickens, T.A. Love, and G.L. Morgan, "Gamma Ray Production Due to Neutron Interactions with Tungsten..., " ORNL-4847 (Jan. 1973).
6. Private communication, P.G. Young.
7. V.M. Bezotosnyi, V.M. Gorbachev, M.S. Shvetsov, and L.M. Surov, *Atomnaya Energiya* 49, 4, pp.239-242 (Oct. 1980).
8. C. Wong, J.D. Anderson, P. Brown, L.F. Hansen, J.L. Kammerdiener, C.M. Logan and B.A. Pohl, "Livermore Pulsed Sphere Program, Program Summary Through July 1971." UCRL-51114, Rev. II, Lawrence Livermore Laboratory (1972).
9. L.F. Hansen, T. Komoto, E.F. Plechaty, B.A. Pohl, G.S. Sidhu, and C. Wong, *Nuclear Science and Engineering*: 62, 550-558 (1977).
10. D.M. Drake, E.D. Arthur, and M.G. Silbert, *Nucl. Sci. Eng.* 65, 49 (1978).
11. G. Haouat, J. Lachkar, J. Sigaud, Y. Patin, and F. Cocu, *Nucl. Sci. Eng.* 65, 331 (1978).
12. J.K. Dickens, T.A. Love, and G.L. Morgan, "Gamma Ray Production from Neutron Interactions with Silicon..., " ORNL-TM-4389 (Dec. 1973).
13. V.C. Rogers, D. Costello, D.R. Dixon, C.G. Hoot, and V.J. Orphan, "Gamma Ray Production Cross Sections for Silicon and Copper from Threshold to 20 MeV," DNA 3818E (2 Oct. 1975).
14. C.M. Logan and T.T. Komoto, "Observed Penetration of 14-MeV Neutrons in Various Materials," UCRL-51663 (Sept. 23, 1974).
15. G.L. Morgan and D.C. Larsen, "The Ti ($n, x \gamma$) Reaction Cross Section for Incident Neutron Energies between 0.3 and 20.0 MeV," ORNL/TM-6323 June 1978.
16. J.K. Dickens, T.A. Love, and G.L. Morgan, "Gamma Ray Production Due to Interactions with Aluminum for Incident Energies Between 0.85 and 20 MeV," ORNL-TM-4232 (June 1973).

17. J.K. Dickens, T.A. Love, and G.L. Morgan, "Gamma Ray Production Due to Neutron Interactions with Fluorine and Lithium for Incident Neutron Energies Between 0.55 and 20 MeV," ORNL-TM-4538 (April 1974).
18. G.N. Maslov, F. Nasyrov, and N.F. Pashkin, *Atomnaya Energiya* 24, 573 (June 1968).
19. D.W. Kneff, B.M. Oliver, and Harry Farrar IV, *Nucl. Sci. Eng.* 92, 491 (1986).
20. E. Goldberg, L.F. Hansen, R.J. Howerton, T.T. Komoto, and B.A. Pohl, "HOTSPUR: Neutron and Gamma Ray Emission from the Transport of 14-MeV Neutrons Through H₂O," UCID-21064 (May 1987).
21. G.L. Morgan and G.T. Chapman, "The 0(n,x γ) Reaction Cross for Incident Neutron Energies Between 6.5 and 20.0 MeV," ORNL-5575 Special (Sept. 1979).
22. T. Yamamoto, Y. Hino, S. Itagaki, and K. Sugiyama, *J. Nucl. Sci. Tech.* 15, 797 (Nov. 1978).
23. V.J. Orphan, C.G. Hoot, and J. John, *Nucl. Sci. Eng.* 42, 352 (1970).
24. F.C. Engesser and W.E. Thompson, *J. Nucl. Eng.* 21, 487 (1967).
25. E. Goldberg et al., *Nucl. Sci. Eng.* 91, 173 (1985).

There is no Figure 1.

COUNTS PER CHANNEL

CHANNEL NUMBER

EXPONENTIAL
ANALYSIS (50000)

EXPONENTIAL
ANALYSIS (50000)

7-00-6

7-00-6

6-4-87

FIGURE 3

NO CALIBRATION

RUN 24 (5-7-87)

COUNTS PER CHANNEL

4-21-57

60Co CALIBRATION
RUN, APR 18, 1957

COUNTS PER CHANNEL

FIGURE 9

CHANNEL NO. = E-013
.0165

7-29-87

FIGURE 5

BLANK (SPHERE OUT)

(RUN NO. 10, 5-5-87)

COUNTS PER CHANNEL

EXPERIMENT 7

TART/SANDY

ELECTRON ENERGY (MeV)

CHANNEL NUMBER

9-03-87

COUNTS PER CHANNEL, NELIS DETECTOR

FIGURE 6

TUNGSTEN,
SPHERICAL SHELL
($\Delta R = 2.54 \text{ cm}$)

EXP'T (6-4-86) (RUN # 17)

ooooo TART/SANDYL (SET 1)

+++++ TART.PSW45/SANDYL SW45.1 (SET 2)

xxxxx WDF/B-F (SET 4)

CHANNEL NUMBER

10

2000

CHANNEL MASTERS

FIGURE 8

Nitrogen 1.1 m. f. p.

All Dimensions in Centimeters

Zone	Density (g/cm ³)	Material	Atomic %
1	0.808	Liquid N ₂	100.0
2	7.9	Fe	68.6
		Cr	20.0
		Ni	8.4
		Si	2.0
		Mn	1.0
3	I.C.T. Low Mass Ass'y and Target		

6-1-87

FIGURE 9

EMPTY LIQUID NITROGEN
SPHERICAL DEWAR

- RUN 13 (5-6-87)

COUNTS PER CHANNEL

..... EXPERIMENT (RUN 13, 5-6-87)

+ + + TARY SANDYL (PSN146/5N146.1)

E (ELECTRON)

CHANNEL NUMBER

200

400

600

6-01-87

FIGURE 10

^{14}N -FILLED SPHERICAL
DWARF
- RUN 14 (5-6-87)

6-30-97

FIGURE 4
GRAPHITE SPHERE
R = 10.16 CM
RUN 2 (5-4-97)

COUNTS PER CHANNEL 10^4

10^3

10

+ in TART/SANDBOX

$(E/\text{electron}) = .033$
.0115 = channel no.

CHANNEL NUMBER

FIGURE 13

SILICON

- RUNS 6+7

(5-5-87)

COUNTS PER CHANNEL

10⁵

10⁴

10²

10

--- TABI/SANDOL (PSSIQ1/SSZ1)

--- EXP'T (RUNS 6+7)

CHANNEL NUMBER

5-18-87

FIGURE 14

TITANIUM

(Run No. 16, 5/6/87)

6-25-87

7-7-87

FIGURE 16

REFLOW SPURGE

R=16.5 CM RUN 31
(5-7-87)

COUNTS PER CHANNEL

NO. 40

5 CITIES + 10 WINDOWS

SEMILOGARITHMIC

NO. 40

NO. 40

6-22-87

FRAME 1

7-9-87

FIGURE 18

H₂O-FILLED GLASS SPHERICAL VESSEL
RUN 11, 5-537

COUNTS PER CHANNEL

ELECTRON ENERGY (MeV)

CHANNEL NUMBER

EXP. RUN 11, 5-537
DATE JANUARY 1987 / SHJ
(FEBRUARY 1987)

SCN 00000000 3 CYCLES 10 DIVISIONS 40000000

DATE 7-9-87 TIME 10:00:00