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EASTERN KENTUCKY UNIVERSITY

DEPARTMENT OF PHYSICS AND ASTRONOMY

Analysis of Gamma-Ray Spectra from Foils Activated in a Range-Thick Lead Target by 800-MeV Protons

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FINAL TECHNICAL REPORT

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ABSTRACT

Approximately 400 gamma-ray spectra have been analyzed to obtain the types and quantities of radioisotopes produced when 800-MeV protons interact with a range-thick lead target. These spectra were obtained from the radioactive decay of product isotopes in lead disks placed at various depths and radial positions within the target. These spectra were analyzed with the computer code HYPERMET and the photopeak areas were reduced to nuclei produced per incident proton per cubic centimeter of material. Product nuclei ranged from atomic mass 160 to mass 206 and over a range of half lives from a few minutes to several weeks. The results of this analysis have been outlined in this report and transmitted on computer disk to Los Alamos National Laboratory. The consistency of these analyses have been confirmed by a comparison of photopeak areas obtained at LANL with the computer code GAMANAL with those from HYPERMET for two gamma-ray spectra. Also, the nuclear production per proton per cm^3 obtained from these two spectra analyzed both at LANL and at ECU have been found to agree to within the statistical accuracy of the peak-fitting programs. This analysis of these 400 gamma-ray spectra has determined the nuclear production per incident proton per cm^3 at five regularly-spaced radial positions and depths up to 40 cm into a range-thick lead target.

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INTRODUCTION

The development of an accelerator-based technique for the production of tritium requires careful consideration of the types and quantities of radioactive nuclei that will be produced. The designs for the accelerator call for protons with GeV-range energies to strike range-thick targets of lead or tungsten. Spallation neutrons produced by this technique then interact with a blanket of material such as ^6Li to produce tritium. The types and quantities of radionuclide produced in this process is estimated analytically using a high-energy nuclear-reaction code coupled with a particle-transport code and with other codes and reaction data to account for low-energy photon and neutron emission and neutron activation. Also, the radioactive decay of the product nuclei must be tracked. These long and complicated code calculations must be validated to insure the accuracy of their predictions.

To aid in this validation, the Neutron Group at Los Alamos National Laboratory (LANL) have performed experiments on range thick assemblies of tungsten and lead. While the analysis of the tungsten target assembly is being undertaken totally at LANL, Eastern Kentucky University (EKU) has contracted to performed the analysis of most of the lead-target data set. This data set consists of approximately 400 gamma-ray spectra taken at LANL during a period of about 2 months following the target irradiation of the lead target by 800 MeV protons.

This analysis has been carried out by David Mullins under the supervision of the Principal Investigator. This report presents a brief description of the procedures, software, data bases, and selection criteria used as well as a summary of the results. A comparison with the results of similar analyses performed by the LANL group have been made to confirm the consistency of analysis techniques. Sample graphical and tabular presentations are included. A complete set of results have been given to Dr. John Ullmann of LANL on computer disks. The results include the tabular results of peak areas from the gamma-ray fitting programs and of type and quantity of identified nuclei in this analysis.

DATA PREPARATION

Since most of the data analysis was performed on personal computers, all necessary data files and spectra files were transported, via internet, to ECU. Two programs, READ_EFF and READ_INC_HEADER, were executed on the P-17 VAX system at LANL to obtain relevant experimental details. The first of these programs generated efficiency tables for the detectors and the second created a file of other experimental parameters. Samples of each are given, respectively, in tables 1 and 2. All of the experiment parameters were compiled into a table that was used at different steps in the data analysis.

Fortunately, the spectra files were of a format that could be read by the computer software supplied by Tennelec/Nucleus for the PCA-II multichannel analyzer system. A sample spectrum is given in Figure 1. As can be seen from this example, some of the spectra contain a large number of gamma-ray photopeaks.

In order to make the data analysis easier to follow, all spectral files were renamed using a convention that readily provided details of the file's contents. This naming convention is as follows:

Figure 2. File Naming Convention for Data Files

This naming convention was used throughout the data analysis at ECU. The foils at increasing radial distances from the axis are designated by a, b, c, d, and e and are specified in more detail in ref. (1).

CALCULATION OF INTERMEDIATE YIELDS

The first step in reducing the gamma-ray spectra into nuclear production required carefully fitting each photopeak using the automated computer code HYPERMET.² As used in the analysis this fits a Gaussian function with an low-energy exponential tail and with a quadratic continuum to each analyzed peak. Parameters used in this program were studied visually to insure that the χ^2 -minimization process properly fit the peaks. After each spectrum was analyzed, additional visual checks were made insure adequate peak fitting.

After the photopeak areas were obtained with HYPERMET they were reduced to a form called the intermediate yields. These intermediate yields consisted of the peak areas with several factors divided into them. These factors were: the live time, the sample volume, the proton fluence, and the efficiency. Once this was completed, a new file was created that contained the photopeak energies, the intermediate yields, and the uncertainties in the intermediate yields. This uncertainty consisted of the statistical error in the peak area and the uncertainty in the efficiency correction and the proton fluence added in quadrature.

The live time was divided into the counts in order to get an activity. This live time was extracted from the data file which contained experimental data using the program READ_INC_HEADER provided by J. Ullmann.

The masses of the foils were provided by J. Ullmann of LANL. Since it was desired to express the results as nuclear production per sample volume, the foil masses were divided by the density of lead ($\rho = 11.3 \text{ g/cm}^3$). The calculated sample volumes were then divided into the photopeak areas for all energies. A table of the foil masses and volumes is given in Table 1.

Since it was desired to calculate the number of nuclides produced per incident proton, it was necessary to divide the counts in the photopeak by the incident proton fluence. The proton fluence was provided by J. Ullmann of LANL. For the 8-hour irradiation the stated fluence was 2.01×10^{15} , and for the 1-hour irradiation, the stated fluence was 3.00×10^{14} .

To complete the calculation of intermediate yields it was necessary to make corrections for the efficiency of the detector for an extended source and for sample self absorption. These calculations had previously been done at LANL. A tabular list of energies and efficiencies including self absorption for each detector at all counting positions was provided by J. Ullmann or generated at ECU using computer codes provided by J. Ullmann. The technique used to obtain these efficiencies is discussed in ref. (1). These lists contained efficiencies for a gamma-ray energy range from 70 to 3700 keV. The efficiencies corrected for the intrinsic and the geometric efficiency of the detector and for the self attenuation and extended nature of the source.

In order to calculate the efficiencies at all photopeak energies in a spectrum, a cubic spline interpolation was performed using the efficiencies in the tables. Once the efficiency was calculated for a particular photopeak energy, it was divided into the photopeak area and the error in the result was propagated. A plot of one of the efficiency tables along with a cubic spline interpolation to the data points is given in Figure 3. Figure 4 is the same plot for a smaller range of energies.

ISOTOPE IDENTIFICATION

Because of the wide range of isotopes that could be produced in each foil, it was necessary in identifying the radioisotopes to make a computer-assisted "first guess" based on the gamma-ray energy. To do this, a table of radioactive nuclides tabulated by Spannier and Ekstrom³ containing gamma-ray energies, branching ratios, and half lives was searched for each photopeak energy in the spectra file to find a match, within an energy interval of $\pm .20$ keV. Since multiple assignments can be made based on only a single gamma-ray energy, other criteria were also used to eliminate false assignments.

The first factor used to narrow the range of assignments made was the half life of the isotope. Since it was known that the shortest time interval from the end of beam to the start of counting was around 700 minutes, it was decided that

isotopes with half lives shorter than 3 hours would be excluded from the search for all sets of foils (1-hour and 8-hour irradiations). It can be shown for foils irradiated for short times that the dominant character of nuclides produced will be of short half life. Similarly, for longer irradiation times, the nuclides produced will be of longer half life. Also, as nuclei decay down the beta decay chain for a given atomic mass, the half lives tends to increase. For these reasons, only isotopes with half lives in the range of 3 hours to 15 hours were accepted for the foils with shorter-irradiation times and isotopes with half lives in the range of 5 hours to 100 days were accepted for the foils for the longer irradiation times.

The other factor used to narrow the search field was the atomic number of the isotope. From previous work done on lead⁴, it was known that, predominantly, isotopes with atomic weights in the range of 150 to 206 were produced in the foils. Because of this, only isotopes with an atomic number in this range were considered as a likely match.

ISOTOPE VERIFICATION

Once the initial guesses were made and they passed the half life and atomic mass tests, another method was used to verify the validity of the selection. This was done in the following way:

1. For each isotope guess, all energies and their associated branching ratios were retrieved from the table generated from Spannier and Ekstrom³.
2. The spectra file was searched for all energies matching energies from the table with a energy range of $\pm .25$ keV.
3. Each activity and uncertainty from the spectra file was divided by their respective branching ratios.
4. At each energy the interval of activity $\pm$ error was compared with all other activities associated with each other photopeak energy.
5. If a user-defined percentage (normally 10%) of the comparisons were matched, the guess was said to be a valid one.

Using this method, several erroneous selections were eliminated.

While it is possible to identify an isotope by its gamma-ray energies alone, it is also possible to verify the identity of the isotope by comparing the activities of the foil at several points in time. From Leo⁵, the activity of an isotope at any time can be expressed as:

$$I = I_0 e^{-\lambda t} \quad (1)$$

where I_0 is the intensity at the initial time, I is the intensity at some time t , and λ is the decay constant. If we plot the natural log of activity versus time from end of bombardment using the activities and times of a single foil, the slope of the

straight line fit to the data points should equal λ , the decay constant. From this, the half life of the isotopes in question could be verified. To this end, two computer codes were written: EXTRACT and LINEVIEW.

EXTRACT was written by the David Mullins⁶ to search spectra files for activities associated with a particular gamma-ray energy. These gamma-ray energies were listed in a table compiled from Spannier and Ekstrom³ and from a table of isotopes by Browne and Firestone⁷. The code divided the activity by the decay constant for the isotope and the branching ratio associated with the gamma ray energy and calculated the natural log of the activity. The output of this code was a table of these activities, the natural log of the activities, the associated errors and the time from end of beam.

The code LINEVIEW, written by David Parsley, an ECU graduate student, read the table created by EXTRACT and displayed, in graphical form, the plot of natural log of activity versus time from end of beam. The code calculated the best-fit line to the points using a chi-square minimization routine and calculated the half life associated with this fit. Since the code EXTRACT used a ± 5 keV energy interval to match a particular photopeak energy, sometimes false assignments were made. These were evidenced by one or more data points that did not conform to the trend of the fit line. These points were assumed to be erroneous. LINEVIEW allowed the user to remove these false data points from the list of valid data points. Once the user was satisfied that the fit was

acceptable, the code created an output file that contained the photopeak energy and the calculated half life.

Simple decay curves were used initially to identify an isotope. The functional fits for these curves were straight lines with slopes equaling the half life of the isotope in question. Figures 5 through 8 show straight line fits for several energies that correspond to a single isotope. All the half-lives agree with 10% of each other. This indicated a positive match. Sometimes, it became necessary to use more complex curves where two separate half lives were present in the time curve. These curves were used only when the two half lives contained in the curve were substantially different so that each component of the curve could be used independently to represent each half-life. This was usually the case for two component curves where a very short decay($t_{1/2} \sim 1$ hour) was followed by a much longer decay($t_{1/2} \sim 1$ day). In these cases it was assumed that any contribution from the long-lived isotope would be negligible for countings that were done very shortly after the end of beam and were counted for short times. Similarly, all contribution from the short-lived isotopes would be negligible after several half lives had passed. Figure 9 shows a curve where two components are visible. Figure 10 shows the same curve with the data points corresponding to the long-lived component removed and Figure 11 shows the same curve with all data points corresponding to the short-lived component removed. Curves that contained more than three components were not used as

a basis for isotope identification due to the difficulties in resolving the three decay curves.

When the decays curves had been fit and the slope of the line equaled the half life of the radioisotope in question within 5 percent, it was necessary to pick a data point on the line to use to calculate the yield of the isotope. In most cases, the ideal data point to use was one which lay on the line representing the half life and which had a time from end of beam greater than two half lives of the isotope. This allowed for all very short lived isotopes with gamma ray energies equaling the energy in question to have decayed to the point where any additional contribution was negligible.

For some isotopes, it was possible to match several energies to a single isotope but often only a single match was possible. This was due in most cases to the very small branching ratio of some of the gamma rays. Wherever possible, as many as three gamma rays were associated with an isotope and used for analysis. A summary of the energies used to identify the isotope and the yields and uncertainties at each energy are given later in the text. Since the activities of all gamma ray energies from a given isotope should be nearly equal(after dividing by their respective branching ratios), yields for a single isotope for all gamma-ray energies that varied less than about 5% were used as a confirmation that a correct assignment had been made.

YIELD CALCULATIONS

Because, in some cases, as many as three gamma-ray energies were used to identify the isotope, a weighted average yield for the three(or two) gamma ray energies was calculated. This was done using the following standard equation:

$$\bar{Y} = \frac{\frac{Y_1}{U_1^2} + \frac{Y_2}{U_2^2} + \frac{Y_3}{U_3^2}}{\frac{1}{U_1^2} + \frac{1}{U_2^2} + \frac{1}{U_3^2}}, \quad (2)$$

where Y_1 , Y_2 , and Y_3 are the individual yields at each energy and U_1 , U_2 , and U_3 are their respective uncertainties. The uncertainty for this weighted average is given by:

$$\bar{U} = \left(\frac{1}{U_1^2} + \frac{1}{U_2^2} + \frac{1}{U_3^2} \right)^{-\frac{1}{2}} \quad (3)$$

where U_1 , U_2 , and U_3 are the individual uncertainties in the yields. The weighted average and the uncertainty are listed later in the text.

Because the samples were rapidly decaying immediately after activation, it was decided to correct the yields of each isotope back to a time after end of beam when all these short-lived-decays had ceased(after 10 half lives). For all five experiments, this time was chosen to be the time of counting for the first foil in the experimental set. The yields were also calculated to end of beam(EOB) in order to make direct comparisons with the analysis done by Ullmann and others at LANL.

RESULTS

It was observed that for all foils analyzed there were a larger number of isotopes produced that had atomic weights close to the atomic weight of the target and that fewer isotopes were produced having atomic weights far away from the atomic weight of the target. It was also observed that these yields ranged between $1.0e^{-6}$ to $1.0e^{-3}$ nuclei per proton per cubic centimeter of material. Figure 12 through 15 show the calculated yields as a function of atomic weight for the 8 hour irradiation, position a(on-axis) for the 4 inch through 16 inch foils. It can be seen from these plots that as the depth into the target increases, the number of isotopes identified and the yields of the individual isotopes decrease. Figure 16 shows a plot of the yield of several isotopes produced in

the on-axis position but at different depths into the target. The very drastic drops in the yields can be seen easily in this plot.

Because foils were also placed in different radial positions at each depth into the target, it was also desirable to see how the yields varied for individual isotopes produced in foils at the depth into the target but at different radial positions. Figure 17 show the yields at 8 inches into the target but at the radial position b, one place off axis. This can be compared to Figure 13. Figure 18 shows the yield of two isotopes produced in the 8-inch foils at different radial positions. Figure 19 shows several yields for the 8-inch foils at the radial positions 'a' and 'b'. It should be noted that there are dramatic drops in the yields going from position 'a' to position 'b'. In fact, these isotopes were not produced in the other radial positions for the same depth into the target.

COMPARISON WITH SIMILIAR LANL ANALYSES

Prior to the ECU involvement LANL had analyzed several of the disks that had been activated. A comparison with two of these analyses have been made to insure consistency of analysis. These two disks were from position 'a' for 4- and 8-inch distances into the target. Four comparisons have been made. First, figures 20 and 21 show the ratio of the photopeak areas determined by LANL using the computer code GAMANAL to the same photopeaks found by ECU

using the code HYPERMET. The results show a spread of a factor of two or more for many photopeaks. However, this is very misleading because the errors in the photopeak fitting (a statistical error) have not been included and all photopeaks were not used in the analysis of nuclear yields.

Figures 22 and 23 give a plot of all gamma-ray areas with errors. Notice that nearly all of the peak areas agree within the range of the error bars. Figures 24 and 25 show a similar plot using only those gamma rays used in determining nuclear production. And finally, figures 26 and 27 show the residuals between the two data sets. The residuals are defined as follows:

$$R = \frac{(A_G - A_H)}{(E_G + E_H)^{1/2}} \quad (4)$$

where A_G and A_H are the GAMANAL and HYPERMET peak areas, respectively, and E_G and E_H are the associated errors in the peak fitting. This figure shows that virtually all photopeak areas agree to within three standard deviations. Also, there are roughly as many GAMANAL areas that are greater than HYPERMET areas as there are smaller. Therefore, the two analyses are consistent.

CONCLUSIONS

Approximately 400 gamma-ray spectra have been analyzed to obtain the types and quantities of radioisotopes produced when 800-MeV protons interact with a range-thick lead target. These spectra were obtained from the radioactive decay of product isotopes in lead disks placed at various depths and radial positions within the target. These spectra were analyzed with the computer code HYPERMET and the photopeak areas were reduced to nuclei produced per incident proton per cubic centimeter of material. The radioisotopes identified were essentially the same as those produced by 0.84, 1.00 and 1.42-GeV protons on lead reported in reference (6). The results of this analysis are outlined in this report and have been transmitted on computer disk to Los Alamos National Laboratory. The consistency of these analyses have been confirmed by a comparison of photopeak areas obtained at LANL with the computer code GAMANAL with those from HYPERMET for two spectra. Also, the nuclear production per proton per cm^3 obtained from these two spectra analyzed both at LANL and at ECU have been found to agree to within the statistical accuracy of the peak-fitting programs. Therefore, the analysis of these 400 gamma-ray spectra have been completed resulting in a determination of the nuclear production at various radial positions and depths in a range-thick lead target.

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**Table 1. Sample Efficiency Table Created by Using
Computer Code READ_EFF**

90.00000	0.5772E-02
100.00000	0.7986E-02
110.00000	0.1021E-01
120.00000	0.1228E-01
130.00000	0.1410E-01
140.00000	0.1563E-01
150.00000	0.1686E-01
160.00000	0.1782E-01
170.00000	0.1854E-01
180.00000	0.1905E-01
190.00000	0.1938E-01
200.00000	0.1959E-01
225.00000	0.1937E-01
250.00000	0.1876E-01
275.00000	0.1798E-01
300.00000	0.1715E-01
325.00000	0.1634E-01
350.00000	0.1557E-01
375.00000	0.1486E-01
400.00000	0.1421E-01
425.00000	0.1360E-01
450.00000	0.1306E-01
475.00000	0.1255E-01
500.00000	0.1209E-01
550.00000	0.1128E-01
600.00000	0.1059E-01
650.00000	0.9997E-02
700.00000	0.9480E-02
750.00000	0.9027E-02
800.00000	0.8624E-02
850.00000	0.8264E-02
900.00000	0.7940E-02
950.00000	0.7646E-02
1000.00000	0.7375E-02
1050.00000	0.7128E-02
1100.00000	0.6900E-02
1150.00000	0.6688E-02
1200.00000	0.6490E-02
1400.00000	0.5816E-02
1600.00000	0.5275E-02
1800.00000	0.4826E-02
2100.00000	0.4274E-02
2500.00000	0.3695E-02
2900.00000	0.3238E-02
3300.00000	0.2868E-02
3700.00000	0.2563E-02

**Table 2. Sample Data Table Created by
Using Computer Code READ_INC_HEADER**

File = header_8hr_pos4a.txt					EOB= 281.7248 MDT			
Data File	Foil	Cnt	Time	Delta	Length	Detector	Gain	Int.
gb:303_059.92	227	303.3876	31194.40	m	200.00	m	76 s 10	0.500 0.169
gb:311_015.92	227	311.1452	42365.43	m	200.00	m	76 s 10	0.500 0.184
gb:317_087.92	227	317.6592	51745.56	m	400.00	m	76 s 10	0.500 0.186
gb:296_012.92	227	296.0202	20585.39	m	200.00	m	42 s 16	0.500 0.288
gb:284_058.92	227	284.3137	3728.01	m	50.00	m	42 s 20	0.500 -0.091
gb:284_106.92	227	284.5872	4121.85	m	50.00	m	42 s 20	0.500 -0.087
gb:285_084.92	227	285.6045	5586.77	m	50.00	m	42 s 18	0.500 -0.129
gb:286_050.92	227	286.3123	6606.04	m	50.00	m	42 s 18	0.500 -0.116
gb:287_010.92	227	287.0150	7617.92	m	50.00	m	42 s 18	0.500 -0.084
gb:287_145.92	227	287.7721	8708.16	m	50.00	m	42 s 18	0.500 -0.097
gb:288_063.92	227	288.4691	9711.78	m	50.00	m	42 s 18	0.500 -0.160
gb:289_015.92	227	289.1646	10713.34	m	50.00	m	42 s 18	0.500 -0.120

Table 3. Masses and Volumes for All Experimental Foils

Foil Number	Position/ Irradiation time	Mass (g)	Volume (cc)
44	(0C/8hr)	3.284	0.290
45	(0D/8hr)	3.097	0.273
47	(0E/8hr)	3.354	0.296
48	(4B/8hr)	3.594	0.317
54	(8B/8hr)	3.275	0.289
57	(8C/8hr)	3.228	0.285
58	(8D/8hr)	3.635	0.321
59	(8E/8hr)	3.296	0.291
90	(12B/8hr)	3.303	0.292
94	(16B/8hr)	3.240	0.286
95	(16C/8hr)	3.222	0.284
96	(16E/8hr)	3.389	0.299
97	(16D/8hr)	3.263	0.288
173	(16B/1hr)	3.634	0.321
177	(12B/1hr)	3.583	0.316
185	(0C/1hr)	3.356	0.296
216	(4A/1hr)	1.643	0.145
217	(4B/1hr)	1.629	0.144
218	(16A/1hr)	1.722	0.152
219	(12A/1hr)	1.667	0.147
220	(8A/1hr)	1.642	0.145
221	(16A/8hr)	1.687	0.149
222	(0B/1hr)	1.662	0.147
227	(4A/8hr)	1.646	0.145
228	(8A/8hr)	1.621	0.143
229	(12A/8hr)	1.668	0.147
389	(0B/8hr)	1.625	0.143

Filename: c:\lan1\spectra\x296078.pca

F1-Acquire F2-Erase F3-Preset F4-Expand F5-Ident F6-Load F7-Save Esc-ROI

Figure 1. Sample Spectrum Viewed on PCA-II by Tennelec/Nucleus

(for Detector 76, Shelf 10, 20 mil foils)
Figure 3. Plot of Efficiency vs. Photopeak Energy

(for Detector 76, Shelf 10, 20 mil foils)
Figure 4. Plot of Efficiency vs. Photopeak Energy

Figure 5. Straight Line fit From Code Lineview

Figure 6. Straight Line fit From Code Lineview

Figure 7. Straight Line fit From Code Lineview

Figure 8. Straight Line fit From Code Lineview

Figure 9. Two Component Fit From Code Lineview

Figure 10. Two Component Curve With Long Component Removed

Figure 11. Two Component Curve With Short Component Removed

Figure 12. Plot of Yield at EOB vs. Atomic Weight for 8 Hour Irradiation
(for 4 inch foil, position a)

Figure 13. Plot of Yield at EOB vs. Atomic Weight for 8 Hour Irradiation
(for 8 inch foil, position a)

Figure 14. Plot of Yield at EOB vs. Atomic Weight for 8 Hour Irradiation
(for 12 inch foil, position a)

Figure 15. Plot of Yield at EOB vs. Atomic Weight for 8 Hour Irradiation
(for 16 inch foil, position a)

Figure 16. Plot of Yield at EOB vs Distance in Target for 8 Hour Irradiation
(all yields from position 'a' foils)

Figure 17. Plot of Yield at EOB vs. Atomic Weight for 8 Hour Irradiation
(for 8 inch foil, position b)

Figure 18. Plot of Yield vs. Radial Position in Target for 8 Hour Irradiation
(foils are 8 inch position in target)

Figure 19. Plot of Yield vs. Radial Position for 8 Hour Irradiation
(foils are 8 inch position in target)

Figure 20. Plot of the Ratio of LANL to ECU Yields vs. Energy
(Position 4A, 8 Hour Irradiation)

Figure 21. Plot of the Ratio of LANL to EKV Yields vs. Energy

(Position 8A, 8 Hour Irradiation)

Figure 22. Comparison of γ -ray Yields from GAMANAL and HYPERMET Analyses
(Position 4A, 8 Hour Irradiation)

Figure 23. Comparison of γ -ray Yields from GAMANAL and HYPERMET Analyses
(Position 8A, 8 Hour Irradiation)

Figure 24. Comparison of γ -ray Yields from GAMANAL and HYPERMET Analyses

(Position 4A, 8 Hour Irradiation)

Figure 25. Comparison of γ -ray Yields from GAMANAL and HYPERMET Analyses
(Position 8A, 8 Hour Irradiation)

**Figure 26. Residual Difference Between GAMANAL
and HYPERMET Outputs**
(Position 8A, 8 Hour Irradiation)

**Figure 27. Residual Difference Between GAMANAL
and HYPERMET Outputs**
(Position 8A, 8 Hour Irradiation)