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^{238}U NEUTRON ELASTIC-SCATTERING CROSS SECTIONS FROM 6.44 TO 8.56 MeV

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ABSTRACT

Measured ^{238}U neutron differential cross sections for elastic scattering (+ inelastic scattering to levels $\leq$ 0.309 MeV) at incident neutron energies of 6.44, 7.54 and 8.56 MeV are presented. The data are in agreement with previous results. ENDF/B MAT 1158 elastic angular distributions are in excellent agreement with experimental results from 6.4 to 8.56 MeV. The ENDF/B 1158 angle-integrated elastic cross section represents a reasonable fit to experimental results from 4 to 8.5 MeV.

INTRODUCTION

Previous reports[1] have given results of a fast-neutron scattering program at ORNL for several elements. Here we present neutron elastic (+ inelastic to levels $\leq$ 0.309 MeV) cross sections for ^{238}U at 6.44, 7.54 and 8.56 MeV. To assist in the evaluation of our data, we briefly discuss our data acquisition and reduction techniques.

For the purposes of discussion, we present our data in graphical form where we compare with the results of others and with ENDF/B (Evaluated Neutron Data File B). Tables of our numerical values of the cross section are given in an appendix.

DATA ACQUISITION

The data were obtained with conventional time-of-flight techniques. Pulsed (2MHz), bunched (~1 nsec full width at half maximum, FWHM) deuterons accelerated by the ORNL Van de Graaff's interacted with deuterium in a gas cell to produce neutrons by the D(d,n)^{3}He reaction. The gas cell, 2 cm in length, was operated at a pressure of approximately 1.5 atm and gave neutron energy resolutions of the order of $\pm$ 60 keV.

The neutrons were scattered from a solid right circular cylindrical sample of uranium enriched to 99.74 weight % in the 238 isotope. The sample was 1.016 cm in diameter, 2.006 cm in height with a mass of 29.74 gm and was placed at a distance of approximately 10 cm from the gas cell for detector angles greater than 25°. For smaller detector angles the cell-to-sample distance had to be increased to as much as 30 cm in order to shield the detector from neutrons coming directly from the gas cells.

The scattered neutrons were detected by 12.5-cm-diam NE-213 liquid scintillators optically coupled to XP-1040 photomultipliers. The scintillators were 2.5 cm thick. Data were taken with three detectors simultaneously. Flight paths were approximately 5 m with the detector angles ranging from 15° to 140°. The gas-cell neutron production was monitored by a time-of-flight system which used a 5-cm-diam by 2.5-cm-thick NE-213 scintillator viewed by a 58-AVP photomultiplier placed about 4 m from the cell at an angle of 55° with the incident deuteron beam.

For each event a PDP-7 computer was given the flight time of a detected recoil proton event with reference to a beam pulse signal, the pulse height of the recoil proton event, and identification of the detector. The electronic equipment for supplying this information to the computer consisted, for the most part, of standard commercial components. The electronic bias, was set at approximately 700-keV neutron energy, a value chosen to assure good pulse shape discrimination for all accepted pulse heights.

The detector efficiencies were measured by (n,p) scattering from a thin (6-mm-diam) polyethylene sample and by detecting source $D(d,n)^{3}He$ neutrons though only the latter were needed for ^{238}U elastic scattering. Both interactions gave results which agreed with each other and which yielded efficiency vs energy curves that compared well with calculations.[2]

DATA REDUCTION

Central to the data reduction process was the use of a light pen with the PDP-7 computer oscilloscope display programs to extract peak areas from spectra. The light pen made a comparatively easy job of estimating errors in the cross section caused by extreme but possible peak shapes.

The reduction process started by normalizing a sample-out to a sample-in time-of-flight spectrum by the ratio of their monitor neutron peak areas, subtracting the sample-out spectrum, and transforming the difference spectrum into a spectrum of center-of-mass cross section vs excitation energy. This transformation allowed ready comparison of spectra taken at different angles and incident neutron energies by removing kinematic effects. It also made all single peaks have approximately the same shape and width regardless of excitation energy (in a time-of-flight spectrum; single peaks broaden with increasing flight time). A spectrum of the variance based on the counting statistics of the initial data were also computed.

The transformed spectra were read into the PDP-7 computer and the peak stripping was done with the aid of the light pen. A peak was stripped by drawing a background beneath it, subtracting the background, and calculating the area, centroid, and FWHM of the difference. The variance spectrum was used to compute a counting statistics variance corresponding to the stripped peak. Peak stripping errors due to uncertainties in the residual background under the peaks or to the tails of imperfectly resolved nearby peaks could be included with the other errors by stripping the peaks several times corresponding to high, low, and best estimates of this background. Although somewhat subjective, the low and high estimates of the cross sections were identified with 95% confidence limits; these, together with the best estimate,

defined upper and lower errors due to stripping. When a spectrum was completely stripped, the output information was written on magnetic tape for additional processing by a large computer.

Finite sample corrections were performed according to semianalytic recipes whose constants were obtained from fits to Monte Carlo results.[3] The corrections were as large as 80% in the minimum of the elastic differential cross section.

The final error analysis included uncertainties in the geometrical parameters (scatterer size, gas cell to scatterer distance, flight paths, etc.) and uncertainties in the finite sample corrections.

The measured differential elastic-scattering cross sections were fitted by least squares to a Legendre series:

$$\sigma(\mu = \cos\theta) = \sum_{\ell=0} \frac{2\ell+1}{2} a_\ell P_\ell(\mu),$$

the points being weighted by the inverse of their variances excluding the common uncertainty of 7% in absolute normalization. In order to prevent the fit from giving totally unrealistic values outside the angular range of our measurements, we resorted to the inelegant but workable process of adding three points equally spaced in angle between the largest angle of measurement and 175°. The differential cross sections at the added points were chosen to approximate the diffraction pattern at large angles, but were assigned 50% errors.

RESULTS

Elastic Scattering and Inelastic Scattering to Low-Lying Levels

Differential cross sections for predominantly elastic scattering are shown in Figure 1 along with the Legendre fits we used to integrate the distributions over angle. Our resolution was not sufficiently good to

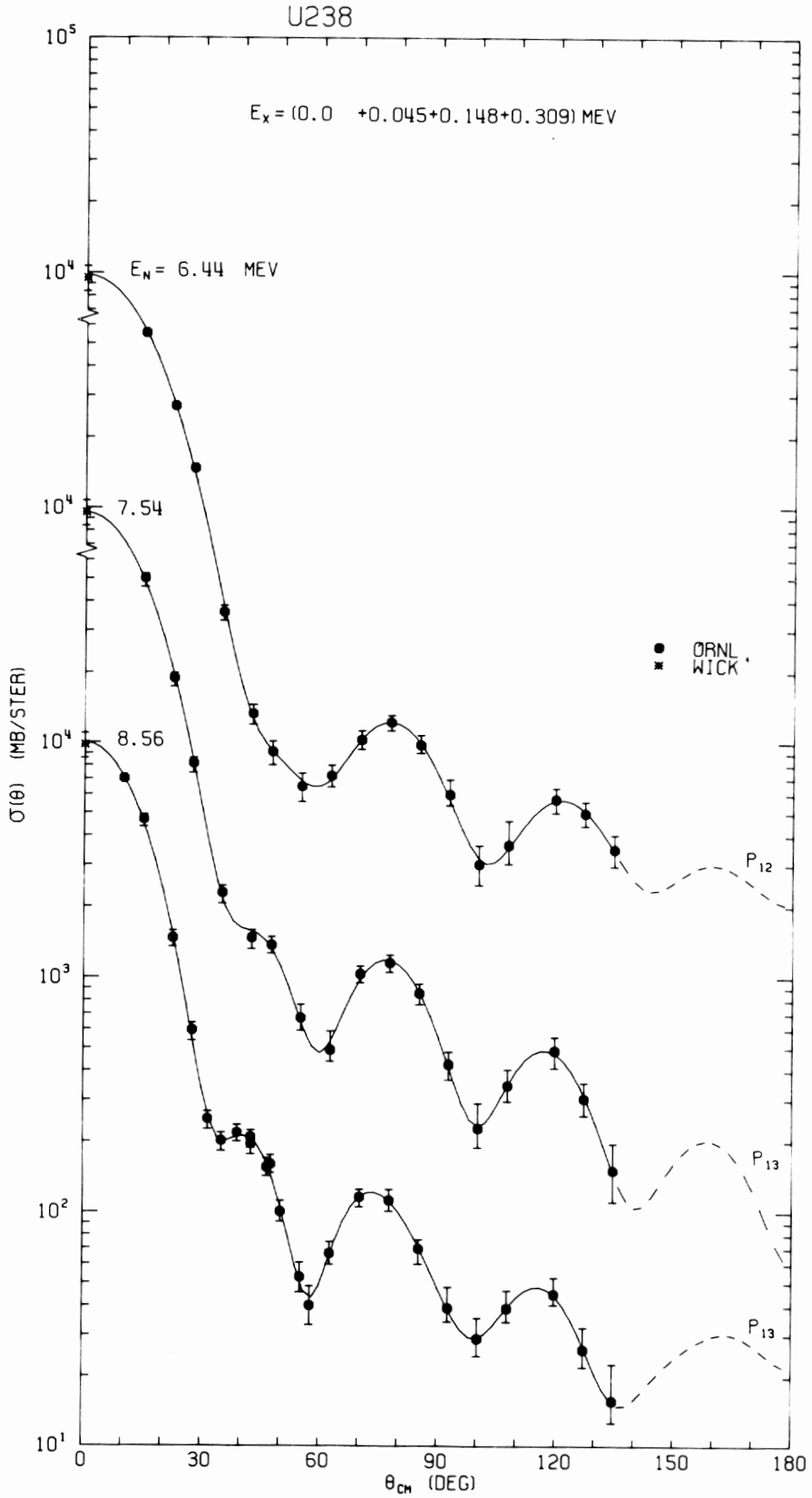

Fig. 1. Our ^{238}U differential cross sections for elastic scattering and inelastic scattering to levels $\leq$ 0.309 MeV. The curves are Legendre fits to the data. The error bars do not include the common 7% uncertainty in absolute normalization. WICK indicates Wick's Limit.

separate inelastic scattering to energy levels up to 0.309 MeV from elastic scattering, but the inelastic contribution is estimated to be less than 1.5 mb/str from the magnitude of the spectra beyond the elastic peak.

Figure 2 compares our differential cross sections for elastic scattering, including inelastic scattering to levels $\leq$ 0.309 MeV, with data of Batchelor et al. (ALD),[4] Walt and Beyster (W+B),[5] and Anikin and Kotukhov (A+K).[6] Angular distributions from ENDF/B MAT 1158, normalized to experimental integrals, are also shown. The integral of Batchelor et al. was used at 7 MeV.

Our data at 8.56 MeV are in good agreement with the small-angle measurements of Anikin and Kotukhov who measured at 8.4 MeV. Our data appear to be consistent with the 7 MeV data. The ENDF/B angular distributions are in good agreement with our data. The good agreement with the 7 MeV data is expected since they were used in the ENDF/B fitting.

Figure 3 compares our angle-integrated elastic cross sections as a function of incident neutron energy with the integrated elastic cross sections of Buccino et al. (DUKE),[7] Walt and Beyster (W+B),[5] and Batchelor et al. (ALD)[4] and with ENDF/B 1158. The ENDF/B curve represents a reasonable fit to the experimental data if the low point of Buccino et al. at 5 MeV is not considered.

CONCLUSIONS

Our data for ^{238}U cross sections for elastic (+ inelastic scattering to levels $\leq$ 0.309 MeV) appear to be consistent with the data of others both in shape and in magnitude. The agreement of ENDF/B 1158 angular distributions with experiment is excellent from 6.4 to 8.5 MeV. The ENDF/B

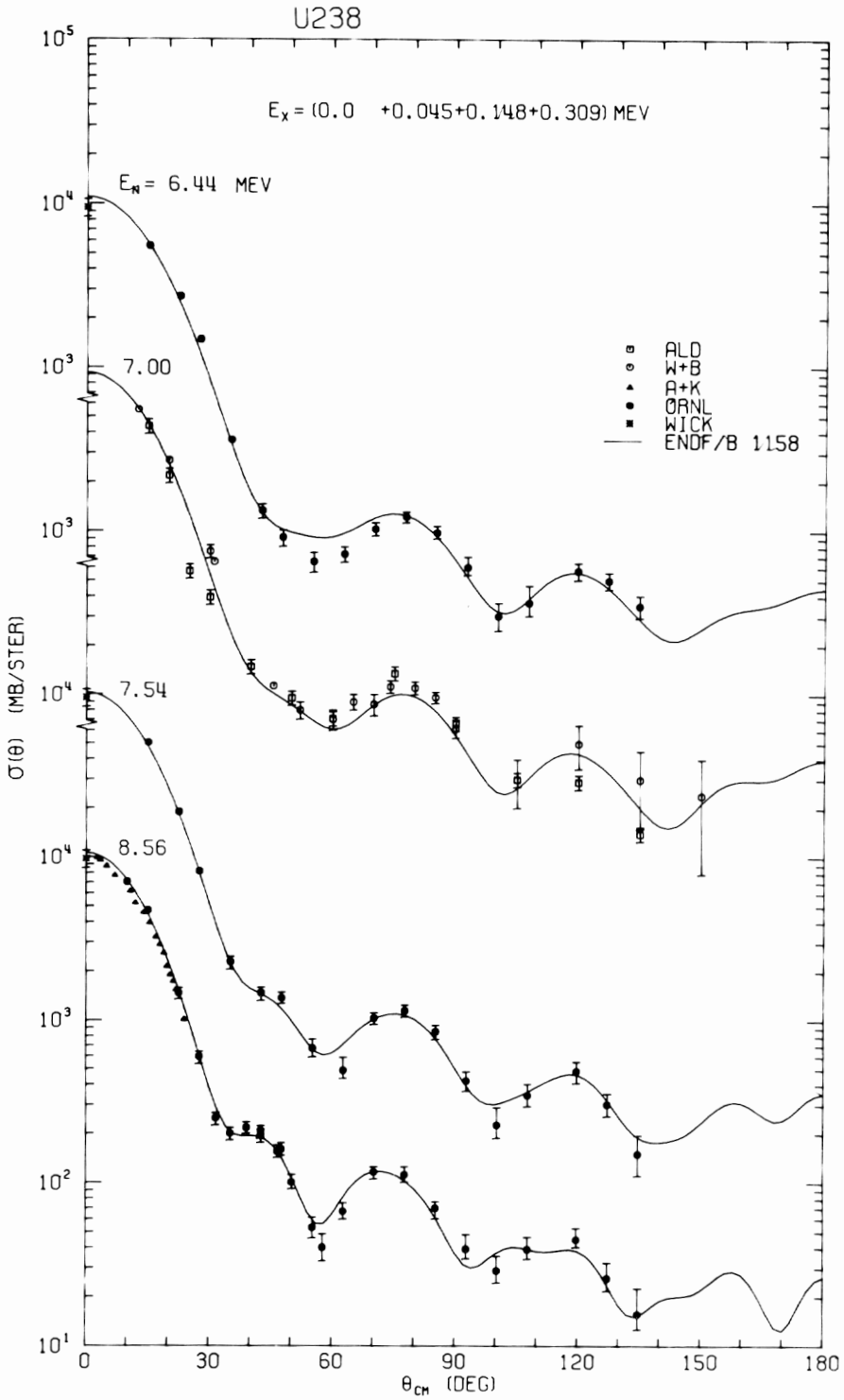

Fig. 2. Our ^{238}U differential cross sections for elastic scattering and inelastic scattering to levels $\leq$ 0.309 MeV compared with the results of others and with ENDF/B-III MAT 1158 elastic angular distributions. WICK indicates Wick's Limit. Error bars on our data do not include the 7% uncertainty in absolute normalization.

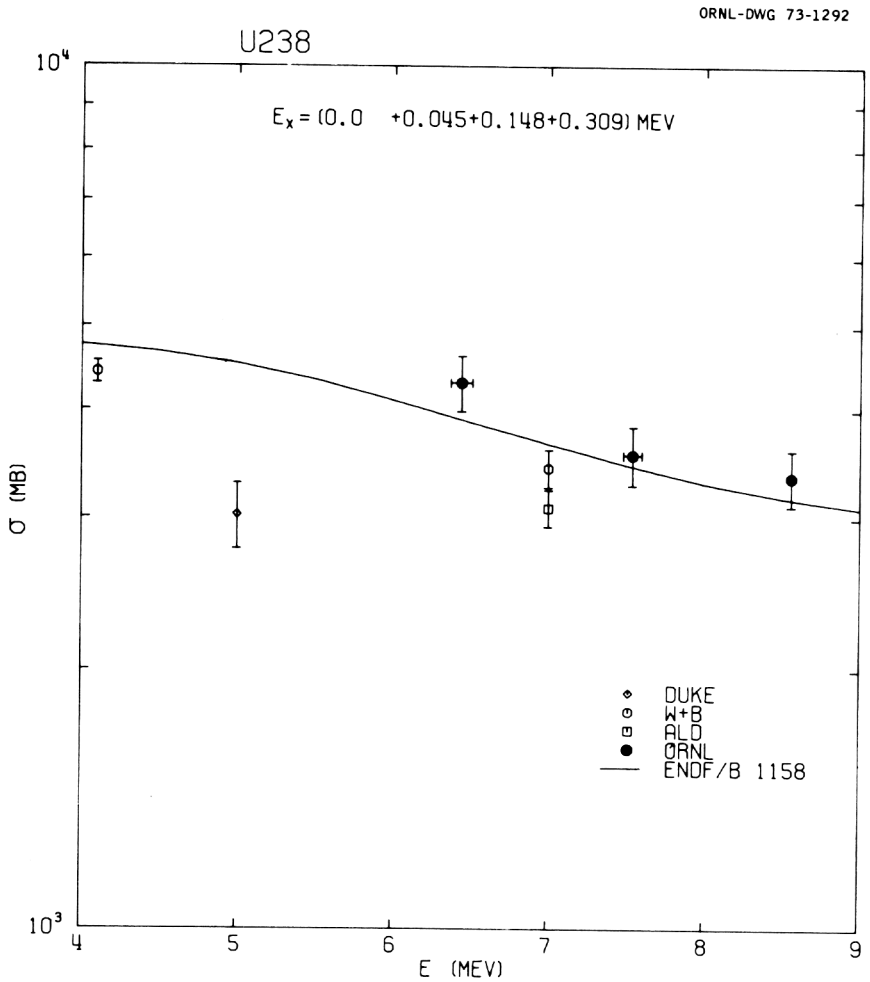

Fig. 3. Our total elastic (+ inelastic to levels $\leq$ 0.309 MeV) cross sections compared with the results of others and with ENDF/B 1158. The 7% uncertainty in absolute normalization is included in our error bars.

angle-integrated elastic cross section is also in reasonable agreement with the experimental results from 4 to 8.5 MeV.

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APPENDIX

Tabulated values of ^{238}U neutron differential cross sections for elastic and inelastic scattering to levels $\leq$ 0.309 MeV.

Our cross sections are tabulated below for incident energies of 6.44, 7.54, and 8.56 MeV. Errors are given in percent and are in general not symmetric. The errors on the points do not include an estimated 7% uncertainty in absolute normalization. The integrated cross sections do contain this error. The total cross section was <u>not</u> measured by us; it is the value we used to compute Wick's Limit.

SCATTERING OF 6.44 +OR-0.07 MEV NEUTRONS FROM U238

LEVEL(S) 0.0 MEV KEY(14) 17 ANGLES
0.045
0.148
0.309

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
15.09	5551.49	4.3	4.8	50503
22.60	2722.41	4.9	5.6	30503
27.62	1480.16	4.5	5.1	50202
35.14	359.76	6.9	7.7	30202
42.67	132.85	9.5	10.4	10202
47.68	91.41	10.6	12.1	50184
55.20	64.91	13.8	13.9	30184
62.72	72.30	10.5	10.6	10184
70.23	102.93	9.2	9.0	50122
77.74	122.32	7.2	8.0	30122
85.24	97.70	10.1	7.8	10122
92.74	60.01	15.8	10.2	50138
100.24	30.27	20.5	18.5	30138
107.73	36.62	26.9	16.9	10138
119.72	57.45	11.5	12.3	50155
127.20	49.98	12.0	11.5	30155
134.68	35.07	15.4	15.3	10155

INTEGRATED X-SEC 4299.98 MB ERROR 7.4 PER CENT

WICKS LIMIT 9482.15 MB/STR ERROR 12.2 PER CENT

TOTAL X-SEC 6.97 B ERROR 5.0 PER CENT

P12 FIT

L	COEF.	ERROR(0/0)
0	684.36401	2.5
1	549.98657	3.0
2	465.76611	3.3
3	396.57666	3.4
4	323.32813	3.7
5	247.88521	4.3
6	171.77385	5.1
7	107.29359	6.8
8	68.77756	8.2
9	42.40038	10.0
10	18.75508	16.7
11	6.33344	33.8
12	1.38336	102.5

SCATTERING OF 7.54 +OR-0.06 MEV NEUTRONS FROM U238

LEVEL(S) 0.0 MEV KEY(14) 17 ANGLES
0.045
0.148
0.309

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	-	RUN
15.07	5019.66	4.1	8.4	50526
22.59	1893.66	5.0	8.2	30526
27.61	818.29	5.0	9.3	51079
35.13	228.51	7.3	10.1	31079
42.67	147.14	7.7	10.4	11079
47.68	136.97	8.4	7.8	50025
55.20	67.13	14.0	11.7	30025
62.72	48.97	20.3	10.7	10025
70.23	103.40	8.1	8.4	50054
77.74	115.17	8.0	8.7	30054
85.24	85.60	9.4	10.4	10054
92.74	42.46	13.5	13.6	50041
100.24	22.65	28.4	17.3	30041
107.73	34.58	17.3	14.5	10041
119.71	48.78	14.4	15.6	50044
127.19	30.48	16.9	15.4	30044
134.67	15.03	30.4	26.3	10044

INTEGRATED X-SEC 3549.06 MB ERROR 7.8 PER CENT

WICKS LIMIT 9536.55 MB/STR ERROR 12.2 PER CENT

TOTAL X-SEC 6.46 B ERROR 5.0 PER CENT

P13 FIT

L	COEF.	ERROR(0/0)
0	564.85107	3.4
1	458.56885	4.0
2	385.18066	4.5
3	334.80786	4.7
4	282.86938	5.0
5	226.94788	5.4
6	170.42656	6.2
7	118.61971	7.4
8	84.62479	8.4
9	60.56223	9.1
10	33.23546	12.6
11	13.99187	21.2
12	4.72127	43.2
13	1.00860	120.0

SCATTERING OF 8.56 +OR-0.05 MEV NEUTRONS FROM U238

LEVEL(S) 0.0 MEV KEY(14) 24 ANGLES
0.045
0.148
0.309

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
10.05	7029.12	5.1	5.1	50553
15.08	4697.91	4.4	7.3	50549
22.60	1470.67	7.3	8.3	30549
27.61	596.20	7.2	10.0	50206
31.64	248.35	7.6	9.5	50322
35.14	200.16	8.5	9.4	30206
39.16	217.13	8.0	8.2	30322
42.66	207.83	7.0	10.3	50318
42.66	194.82	8.5	9.9	10206
46.68	154.40	9.4	8.1	10322
47.68	159.29	9.6	8.2	50271
50.18	100.23	11.3	9.1	30318
55.20	53.01	15.2	13.7	30271
57.71	40.09	20.9	17.3	10318
62.72	66.71	12.2	10.4	10271
70.23	116.02	7.6	9.3	50229
77.74	111.90	11.4	9.9	30229
85.24	69.82	9.3	13.9	10229
92.74	39.22	22.6	12.8	50282
100.24	28.92	22.7	15.7	30282
107.73	39.09	19.0	12.7	10282
119.71	44.92	17.5	10.0	50240
127.19	26.08	24.4	16.0	30240
134.67	15.71	44.2	19.5	10240

INTEGRATED X-SEC 3346.50 MB ERROR 7.4 PER CENT

WICKS LIMIT 9780.61 MB/STR ERROR 12.2 PER CENT

TOTAL X-SEC 6.14 B ERROR 5.0 PER CENT

P13 FIT

L	COEF.	ERROR(0/0)
0	532.61182	2.5
1	425.28149	2.9
2	359.76563	3.2
3	312.92163	3.4
4	270.83569	3.4
5	223.30312	3.6
6	176.19580	3.9
7	130.34929	4.3
8	97.74533	4.7
9	75.09377	4.7
10	48.71053	5.7
11	25.71748	8.2
12	10.91856	14.4
13	2.86917	38.9

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