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CARBON NEUTRON ELASTIC- AND INELASTIC-SCATTERING CROSS SECTIONS FROM 4.5 TO 8.5 MeV

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OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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DECEMBER 1969

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ABSTRACT

Numerical values are given for neutron elastic- and inelastic-scattering cross sections from carbon in the energy range 4.5 to 8.5 MeV. A brief description of the experimental and data reducing techniques is presented to assist in the evaluation of the data. A comparison was made with other data in this energy region, and fairly good agreement was found, particularly with previous time-of-flight data. Our data were also compared with the predictions obtained from the current ENDF/B file of "evaluated" cross sections for carbon. The ENDF/B file was found to reproduce very poorly the data for both elastic and inelastic cross sections. This is not too surprising in view of the rapid changes in the shapes of the cross sections and the paucity of data previously available in this energy region.

INTRODUCTION

Numerical values of neutron elastic- and inelastic-scattering cross sections from carbon were obtained in the range 4.5 to 8.5 MeV. Conventional time-of-flight techniques were used to obtain the data, which were then reduced with the aid of a light pen with the PDP-7 computer.

When our data were compared with other data in this energy region, fairly good agreement was obtained with previous data, particularly with previous time-of-flight data. The predictions obtained from the current ENDF/B file of "evaluated" cross sections for carbon are relatively poor, which is not surprising in view of the resonant structure of both the elastic and inelastic cross sections and the paucity of previously available data in this energy range.

DATA ACQUISITION

The data were obtained with conventional time-of-flight techniques. Pulsed (2 MHz), bunched (~1 nsec full width at half maximum, FWHM) deuterons accelerated by the ORNL Van de Graaff interacted with deuterium in a a gas cell to produce neutrons by the $D(d,n)^3He$ reaction. The gas cells, whose lengths varied from 0.7 to 4 cm and whose pressure was approximately 1.5 atm, gave neutron energy resolutions from 60 to 340 keV, depending on the incident deuteron energy.

The neutrons were scattered from a solid right circular cylindrical sample (2.54 cm in diameter, 2 cm long) placed approximately 10 cm from the gas cell when the detector angles were 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 cell.

The scattered neutrons were detected by 12.5-cm-diam NE-213 liquid scintillators optically coupled to XP-1040 photomultipliers. The scintillators were normally 2.5 cm thick, but their thickness was increased to 5 cm when the 4-cm gas cell was used. Data were taken with a single detector and later with three detectors simultaneously. Flight paths varied from 4 to 6 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 2 m from the cell at an angle of 55° with the incident deuteron beam.

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 in the three-detector system were supplied to an on-line PDP-7 computer. The electronic equipment for supplying this information to the computer consisted, for the most part, of standard commercial components. While gamma rays were discriminated against for both the scattered neutron and the monitor detectors, the discrimination was poor below a neutron energy of 700 keV. A digital bias corresponding to this neutron energy was therefore put into the computer so that two time-of-flight spectra were obtained for each scattered-neutron detector, the spectra corresponding to pulse heights above and below the digital bias. Only the spectra above the bias were used.

The detector efficiencies were measured by (n,p) scattering from a thin (6-mm-diam) polyethylene sample and by detecting neutrons coming directly from the gas cell. Both interactions gave results which were in agreement and which yielded efficiency vs energy curves that compared well with calculations.[1]

DATA REDUCTION

We have developed new methods of data reduction which have both simplified the process and made it more reliable. Central to the data reduction process is the use of a light pen with the PDP-7 computer scope display programs to extract peak areas from spectra. The light pen makes a comparatively easy job of separating multiplets and estimating errors in the cross section due to extreme but possible peak shapes. The time-of-flight spectra are transformed into a center-of-mass cross section as a function of excitation energy in the target nucleus before peak stripping is done. This transformation removes kinematic effects and allows easy comparison of spectra taken at different angles or different incident neutron energies. The second effect of the transformation is to make all the peak shapes and widths approximately the same. In the time-of-flight spectrum the width of the peaks is a rapidly varying function of neutron energy since the energy dispersion changes as a function of flight time. Finally, there is communication between the PDP-7 and larger computers via magnetic tape in order to mimimize the bookkeeping and card punching and hence the errors which accompany such operations.

The reduction process starts 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 cross section (mb/ster/25 keV) vs excitation energy (25 keV/channel). In addition, a spectrum of the variance is computed based on the counting statistics of the initial data.

The transformed spectra are read into the PDP-7 computer from magnetic tape, and the peak stripping is done by means of the light pen. A peak is stripped by drawing a background beneath it and then having the computer calculate the peak area (mb/ster), centroid, and FWHM. The variance spectrum is 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 may 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 are identified with 95% confidence limits for the value of the cross section due to this background. These limits together with the best estimate define upper and lower errors due to stripping. Different upper and lower values of the stripping errors are allowed since the upper and lower estimates of the background are rarely symmetric about the best estimate. When a spectrum is completely stripped, the stripping information is written on magnetic tape for additional processing by a larger computer.

Inelastic cross sections are generally sufficiently isotropic so that finite sample corrections can be made at each angle independently of results at other angles. Correction of the elastic cross section, however, must await the reduction of the entire angular distribution before the finite sample effects can be considered. The corrections are performed according to semianalytic recipes whose constants were obtained from fits to Monte Carlo results, the multiple-scattering correction being much like that proposed by Cox.[2]

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

RESULTS

The Data

The data are presented in Tables 1 through 22 and in Figs. 1 through 22. The curves shown in the figures are the angular distributions obtained from the ENDF/B file of "evaluated" cross sections for carbon and will be discussed later.

Most of the data reported here were taken with a three-detector system placed on a movable platform with detectors about 7.5° apart. In order to avoid some systematic errors in the relative cross sections as a function of angle, adjacent angular segments of 15° were not measured consecutively most of the time. The data at some angles were measured more than once to obtain some information on the reproducibility of our data. We have not attempted to average the data taken at the same angles in order to give the evaluator some information on our ability to reproduce our own data points. The errors given at each angle are not entirely uncorrelated to the errors of adjacent points, in particular for the angles measured simultaneously, but our error analysis did not include any such cross correlation of errors. Not included in the errors shown at each angle is an absolute error of ±7% in the absolute value of the cross sections which is our estimate of the error on the absolute value of our efficiency. This 7% absolute error should not affect the relative shape of the angular distributions.

The integrated cross sections were obtained by performing a Legendre polynomial fit to our data. The Legendre polynomial expansion is necessary in our method of correcting the data for the finite size of the scatterer in the case of elastic scattering. Provided that the Legendre polynomial fit gives "reasonable" cross sections outside the angular range of our data, the corrections for finite size to our data are reasonably independent of the value of the cross sections outside our measured range. All Legendre polynomial fits to our data were visually inspected and found to give, in a subjective manner, acceptable cross sections over the complete angular range. The errors on the integrated cross sections include the ±7% absolute error on the normalization but do not include the error due to possible extreme values of the cross section outside our measured angular range.

Table 1

SCATTERING OF 4.60 +OR- .05 MEV NEUTRONS FROM

LEVEL(S) 0 MEV KEY(11) 10 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN

MULTIPLE SCATTERING CORRECTION DONE

32.42	317.80	5.1	5.6	22255
46.30	242.35	6.0	6.5	22229
58.99	136.53	6.0	6.7	22259
72.51	112.21	7.3	8.5	22232
84.79	85.28	7.3	8.8	22263
97.82	102.34	8.8	10.8	22235
97.85	90.22	7.2	9.4	22252
109.69	92.60	6.4	7.4	22266
122.26	72.03	8.6	9.7	22245
135.59	60.00	8.7	13.4	22249

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1671.74 MB ERROR 7.4 PER CENT

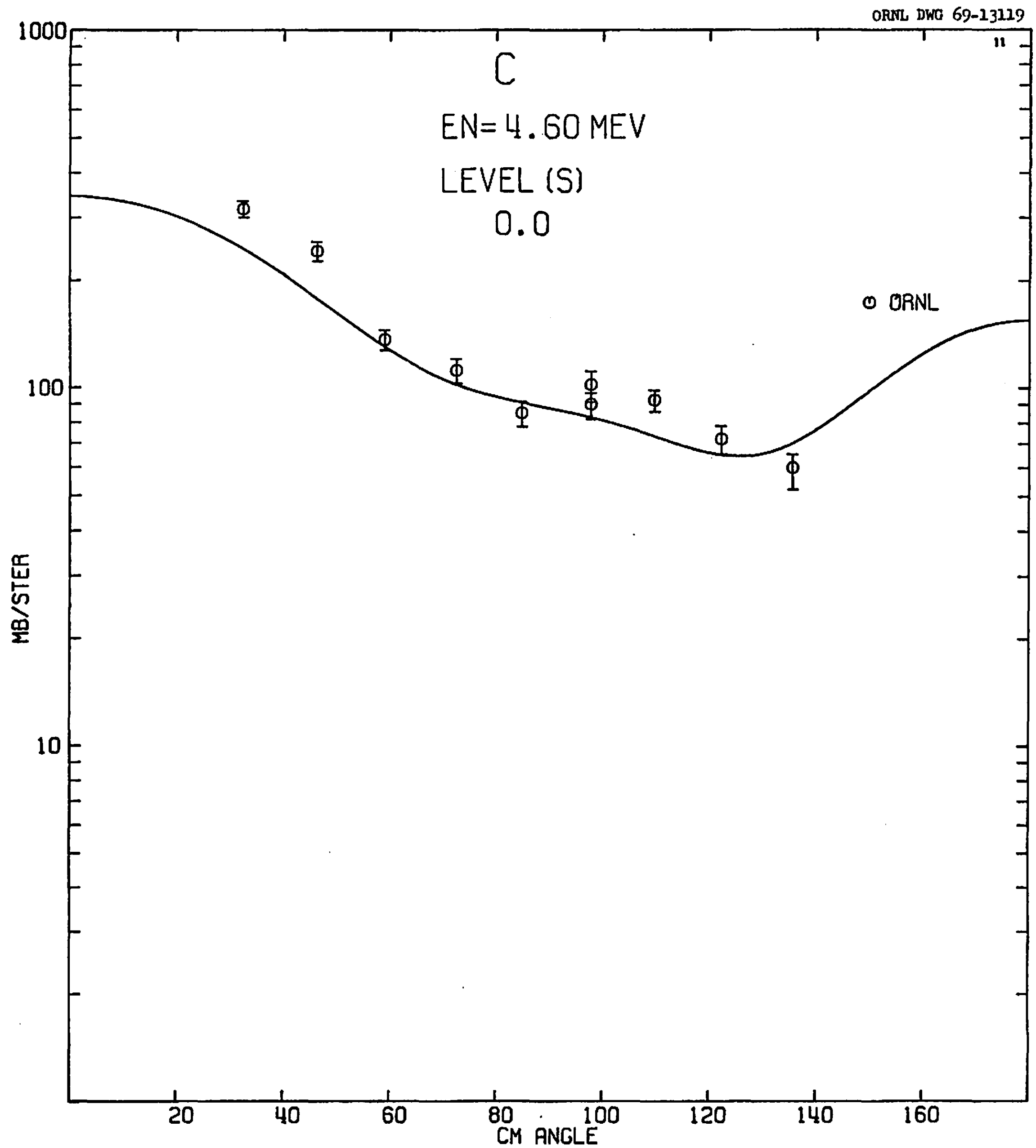

ORNL DWG 69-13119
C
EN= 4.60 MEV
LEVEL (S)
0.0
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 1

Table 2

SCATTERING OF 5.04 +OR- .04 MEV NEUTRONS FROM [illegible]

LEVEL(S) 0 MEV KEY(11) 11 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
32.40	173.65	4.6	5.0	22176
46.30	121.66	5.0	5.3	22216
60.03	93.32	5.3	6.2	22119
72.50	70.74	7.0	6.6	22206
84.77	74.53	5.8	7.3	22152
84.78	69.79	6.3	7.6	22188
94.83	77.24	5.7	5.7	83
97.83	80.46	5.8	6.7	22195
109.66	90.92	6.2	7.6	22156
121.30	75.56	6.0	7.8	22198
133.68	60.86	7.5	6.5	22163

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1139.72 MB ERROR 7.3 PER CENT

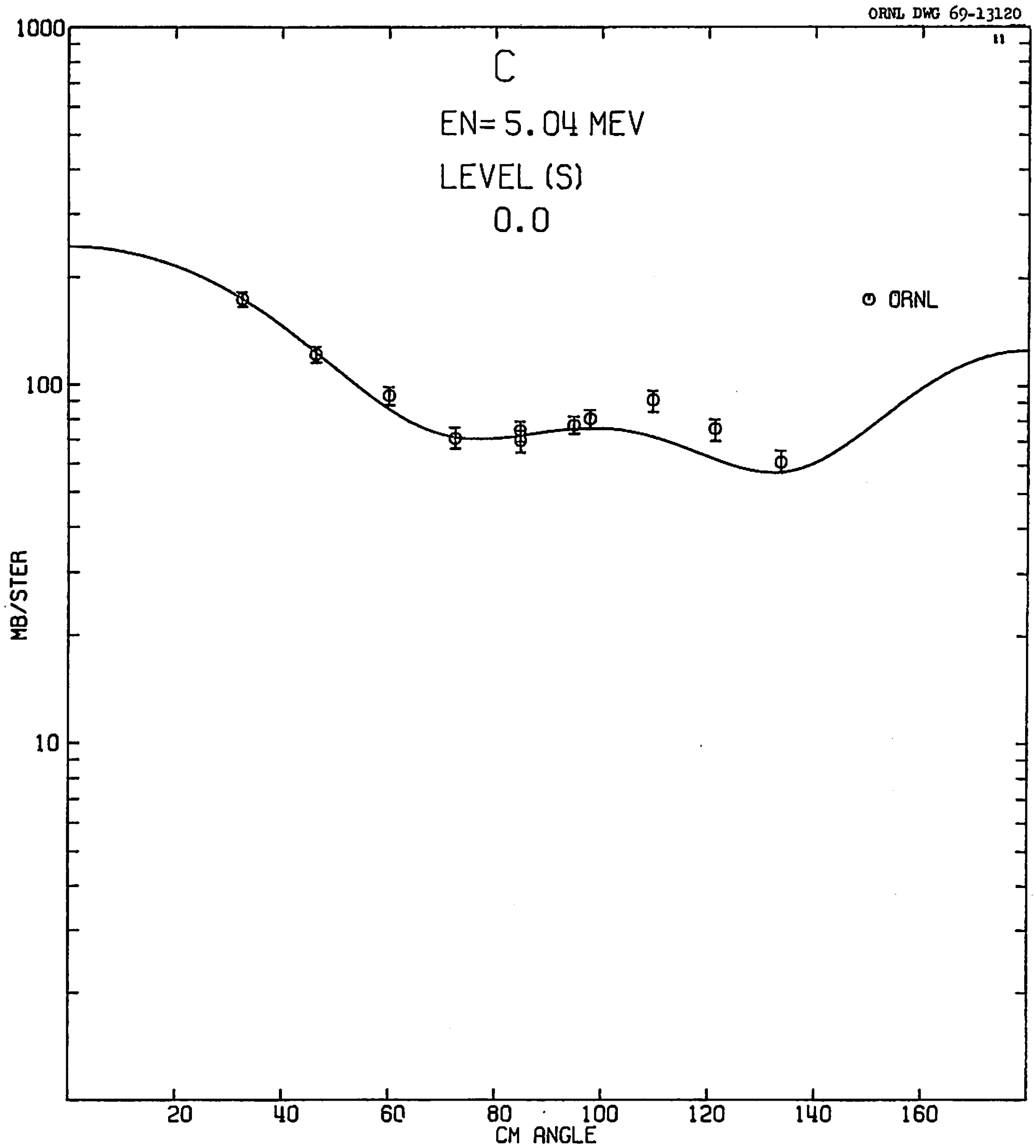

ORNL DWG 69-13120
C
EN= 5.04 MEV
LEVEL (S)
0.0
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 2

Table 3

SCATTERING OF 5.44 +OR- .17 MEV NEUTRONS FROM

LEVEL(S) 0 MEV KEY(11) 24 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(O/O) +	-	RUN

MULTIPLE SCATTERING CORRECTION DONE

23.80	234.37	4.8	7.3	50343
29.71	204.59	4.9	7.1	10256
34.54	184.72	4.4	9.5	50332
34.58	184.47	4.4	5.0	50330
40.42	153.33	4.4	8.3	10332
40.45	158.32	4.4	5.4	10328
40.46	158.92	4.4	4.9	10330
45.23	134.07	4.2	4.7	50317
46.27	126.83	4.9	9.0	30332
51.06	108.71	4.3	4.8	10317
56.86	91.42	4.4	5.0	30317
61.08	75.93	4.6	5.6	50305
66.80	63.27	4.8	6.0	10305
72.49	58.79	4.9	5.8	30305
76.58	51.63	5.0	2.0	50294
82.23	58.70	4.9	6.2	10294
87.81	68.53	4.8	5.5	30294
92.84	69.55	4.8	5.8	50281
94.83	67.43	5.6	5.6	120
98.32	76.71	4.8	5.4	10281
103.77	81.57	4.8	5.7	30281
106.72	72.00	5.0	6.8	50268
112.09	67.95	5.1	10.2	10268
117.44	68.27	5.1	6.6	30268

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1107.38 MB ERROR 7.1 PER CENT

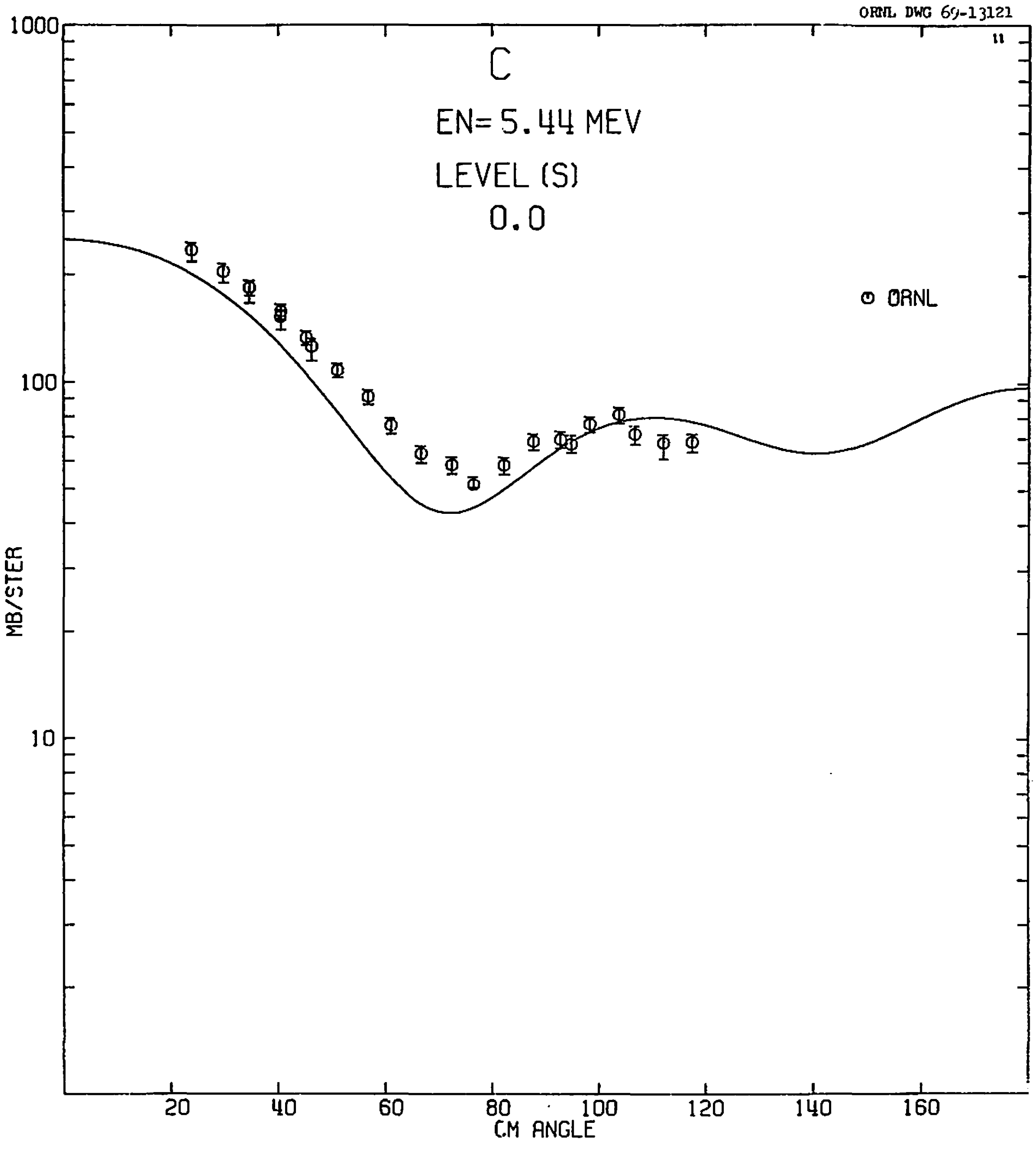

ORNL DWG 69-13121
C
EN= 5.44 MEV
LEVEL (S)
0.0
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 3

Table 4

SCATTERING OF 5.56 +OR- .05 MEV NEUTRONS FROM SI

LEVEL(S) 0 MEV KEY(11) 9 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	-	RUN
MULTIPLE SCATTERING CORRECTION DONE				
32.43	159.25	4.8	7.0	22318
46.31	104.80	5.2	7.4	22295
54.76	80.64	5.6	7.7	22314
64.23	55.06	6.2	10.6	22290
79.71	49.00	7.0	13.6	22311
94.82	71.33	6.6	6.6	22298
109.67	94.02	6.2	7.6	22308
122.26	89.69	5.6	6.4	22302
135.59	68.70	6.9	8.1	22305

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1060.49 MB ERROR 7.4 PER CENT

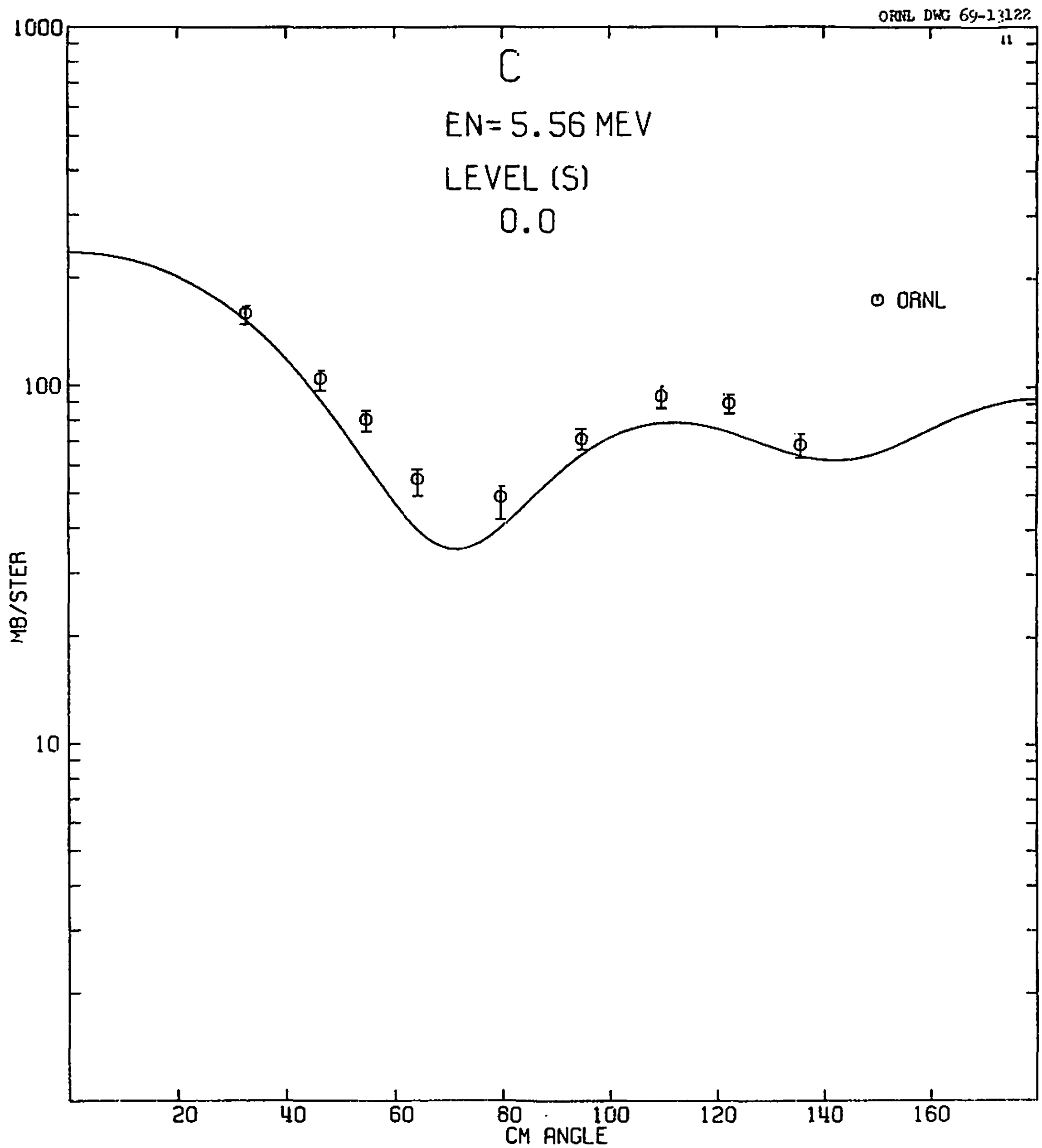

ORNL DWG 69-13122
C
EN=5.56 MEV
LEVEL (S)
0.0
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 4

Table 5

SCATTERING OF 6.01 +OR- .07 MEV NEUTRONS FROM

LEVEL(S) 0 MEV KEY(11) 17 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(O/O) +	-	RUN
		MULTIPLE SCATTERING CORRECTION DONE		
16.24	249.98	4.9	5.3	150483
24.33	213.07	4.4	4.5	130483
29.71	189.60	4.3	4.7	150453
37.75	142.68	4.4	4.6	130453
45.74	102.43	4.6	5.2	110453
51.03	87.24	4.6	5.3	150461
58.92	53.91	5.4	5.4	130461
66.75	33.85	6.4	6.9	110461
74.51	33.15	6.5	7.2	150446
82.19	38.37	6.1	6.9	130446
89.78	50.20	5.9	6.6	110446
97.30	71.60	5.1	6.0	150467
104.72	81.98	5.0	5.6	130467
112.07	83.55	5.2	5.7	110467
123.67	81.93	5.5	6.2	150474
130.83	72.54	6.4	6.9	130474
137.92	60.95	6.1	8.1	10474

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 965.32 MB ERROR 7.1 PER CENT

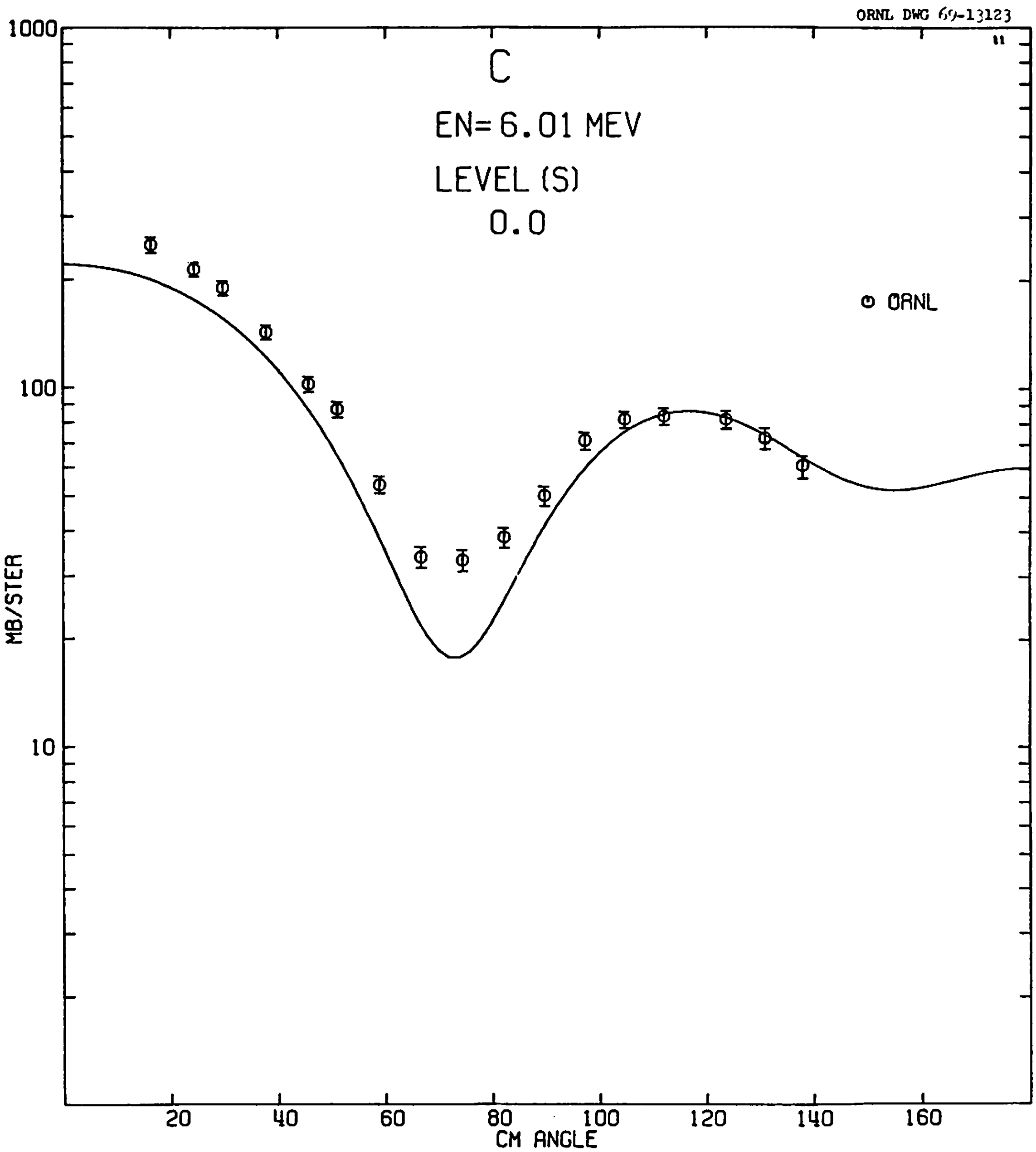

ORNL DWG 69-13123
C
EN= 6.01 MEV
LEVEL (S)
0.0
ORNL
MB/STER
CM ANGLE
1000
100
10
20
40
60
80
100
120
140
160

Figure 5

Table 6

SCATTERING OF 6.01 +OR- .07 MEV NEUTRONS FROM [illegible]

LEVEL(S) 4.430 MEV KEY(21) 10 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
MULTIPLE SCATTERING CORRECTION DONE				
17.81	29.00	19.1	18.8	150483
26.61	27.88	15.5	15.8	130483
32.48	27.40	13.3	13.3	150453
41.21	26.26	13.2	13.7	130453
49.82	23.57	14.3	14.8	110453
55.46	26.18	14.9	14.8	150461
63.89	23.43	16.4	16.5	130461
72.16	19.07	21.3	21.2	110461
80.21	22.58	25.1	25.5	150446
88.05	18.85	28.5	28.9	130446

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 249.15 MB ERROR 40.7 PER CENT

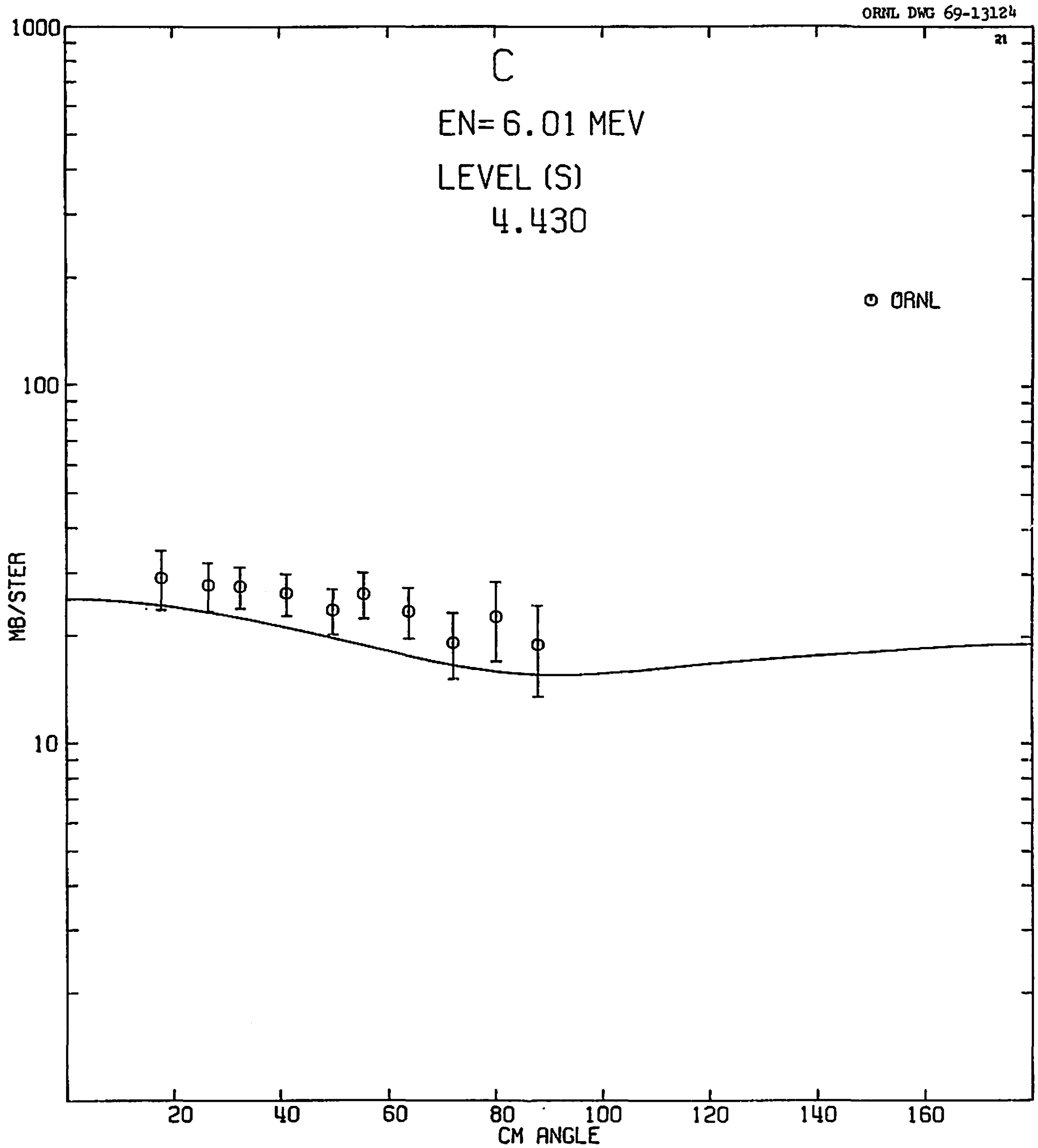

ORNL DWG 69-13124
21
C
EN= 6.01 MEV
LEVEL (S)
4.430
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 6

Table 7

SCATTERING OF 6.37 +OR- .13 MEV NEUTRONS FROM C

LEVEL(S) 0 MEV KEY(11) 25 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	-	RUN
MULTIPLE SCATTERING CORRECTION DONE				
24.33	339.25	3.9	5.9	110223
29.72	237.81	4.0	6.1	110235
29.72	246.82	4.0	5.9	110237
34.55	172.25	4.0	5.7	150319
35.08	168.35	4.0	5.7	110250
40.43	107.66	4.2	5.5	110319
46.30	69.0M	4.7	7.1	130319
50.54	42.52	5.3	8.0	150300
50.54	42.77	6.6	9.2	150304
56.32	28.17	6.3	6.9	150065
56.34	33.86	6.2	9.0	110300
56.35	35.71	5.8	10.0	110304
62.11	37.04	5.7	10.7	130300
62.12	36.91	5.7	10.6	130304
66.28	39.46	5.4	10.7	150288
71.97	51.94	5.1	9.9	110288
77.62	62.87	4.7	6.9	130288
81.70	62.05	5.0	7.3	150276
87.28	73.66	4.7	6.8	110276
92.82	81.03	4.6	6.4	130276
96.82	78.40	4.6	7.8	150211
102.28	80.22	4.7	7.5	110211
107.69	87.16	4.6	7.0	130211
112.09	69.55	4.8	7.4	110263
122.25	72.07	4.9	5.7	140065

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1158.48 MB ERROR 7.2 PER CENT

ORNL DWG 69-13125

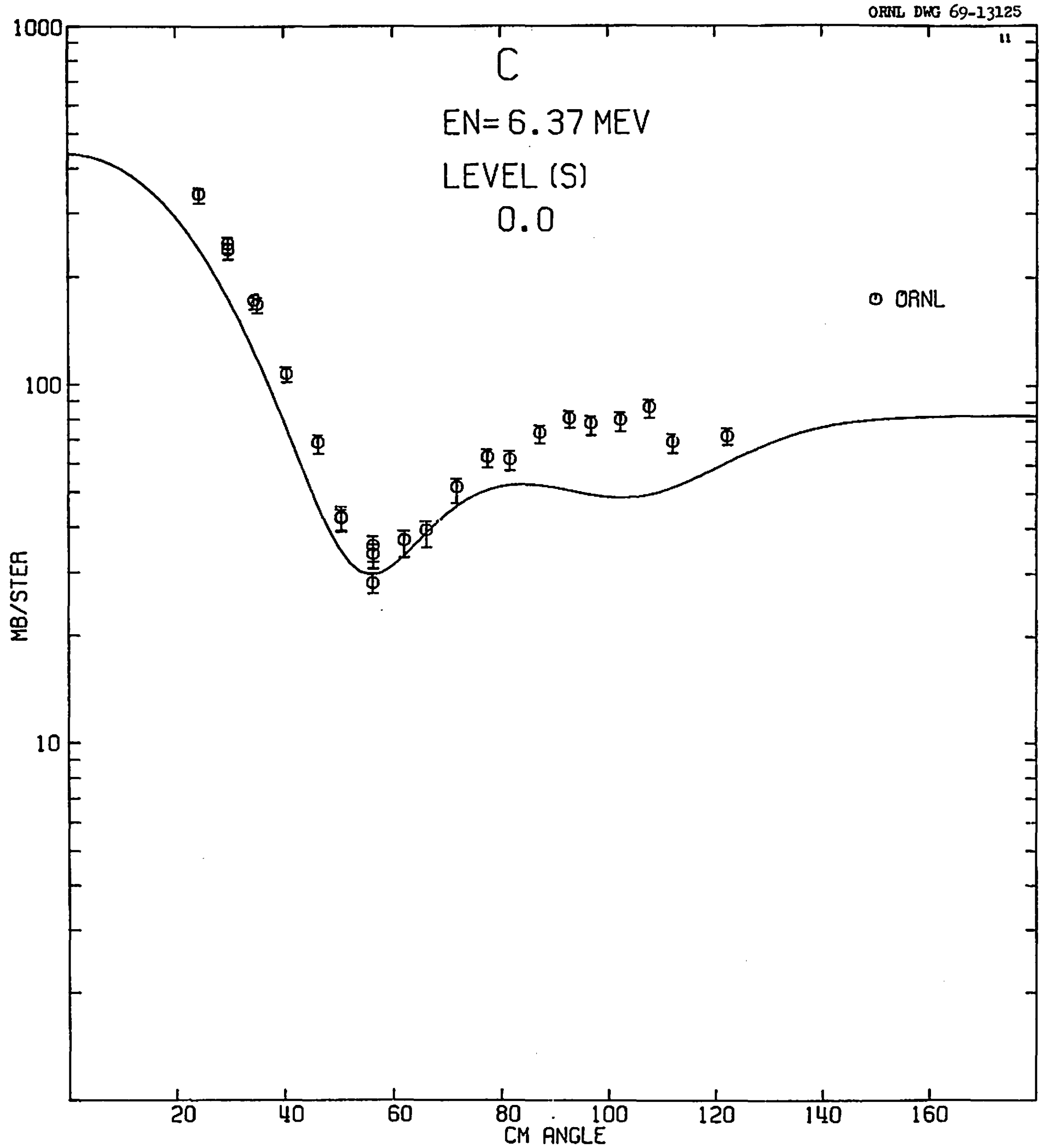


Figure 7

Table 8

SCATTERING OF 6.37 +OR- .13 MEV NEUTRONS FROM C

LEVEL(S) 4.430 MEV KEY(21) 25 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(O/O) +	-	RUN
MULTIPLE SCATTERING CORRECTION DONE				
26.20	23.25	8.8	8.8	110223
31.96	22.02	9.3	10.2	110235
31.97	21.39	9.3	9.3	110237
37.13	22.55	8.2	8.0	150319
37.70	23.83	8.9	8.6	110250
43.40	20.68	8.2	7.9	110319
49.61	21.97	8.4	8.4	130319
54.08	19.86	13.9	7.7	150300
54.10	20.95	9.4	9.4	150304
60.18	19.91	9.7	8.3	110300
60.19	20.62	9.7	8.9	110304
60.28	24.16	10.0	12.3	150065
66.21	20.06	11.1	9.1	130300
66.24	21.40	10.0	9.2	130304
70.55	19.92	11.2	9.9	150288
76.47	17.59	11.2	11.2	110288
82.30	17.64	12.6	11.0	130288
86.45	18.71	12.4	11.5	150276
92.14	16.16	13.2	12.8	110276
97.69	16.48	16.0	14.6	130276
101.66	18.10	16.2	14.1	150211
107.14	15.05	19.6	15.0	110211
112.45	19.34	19.3	16.2	130211
116.75	18.61	20.8	19.5	110263
126.60	18.80	25.7	25.7	140065

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 236.26 MB ERROR 8.7 PER CENT

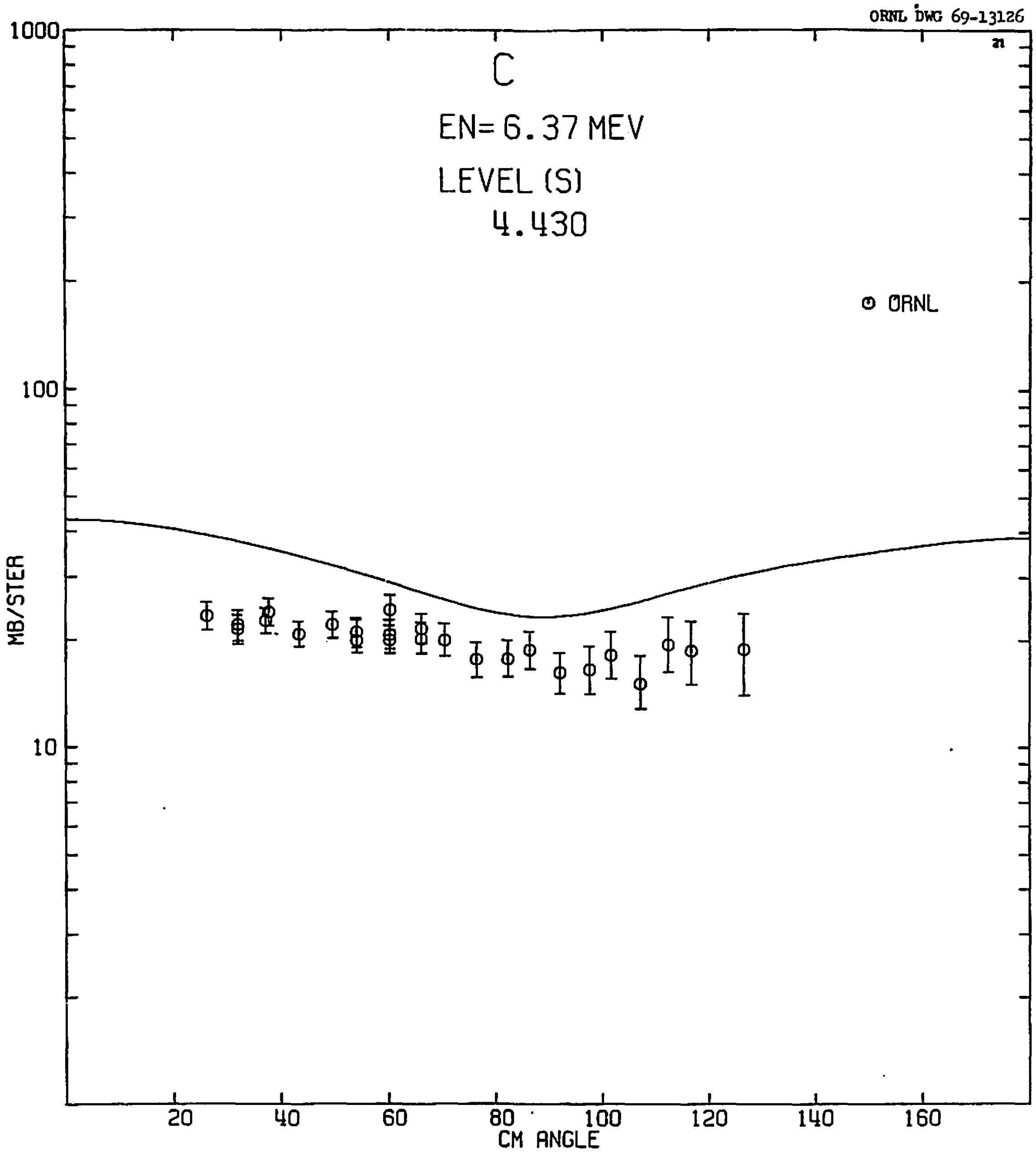

ORNL DWG 69-13126
C
EN= 6.37 MEV
LEVEL (S)
4.430
ORNL
MB/STER
CM ANGLE
1000
100
10
20
40
60
80
100
120
140
160

Figure 8

Table 9

SCATTERING OF 6.44 +OR- .07 MEV NEUTRONS FROM C

LEVEL(S) 0 MEV KEY(11) 22 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
	MULTIPLE SCATTERING CORRECTION DONE			
16.24	337.63	4.1	4.4	150490
24.33	240.81	4.7	4.3	130490
29.71	189.50	3.9	4.0	150189
37.75	122.25	4.1	4.5	130189
45.74	76.98	4.8	5.6	110189
51.03	58.05	4.8	5.2	150175
58.93	42.96	5.2	5.3	130175
66.76	41.13	5.6	6.5	110175
74.52	48.94	5.2	5.8	150113
82.19	54.27	4.8	6.3	130113
89.79	54.11	5.1	6.9	110113
97.30	52.80	5.2	7.2	150128
104.74	42.69	6.4	6.8	130128
112.09	38.11	6.2	6.7	110128
123.68	39.03	6.0	8.2	150172
123.69	41.75	7.1	8.4	150143
123.69	39.47	6.8	6.9	150153
130.83	38.96	6.7	5.7	130143
130.84	37.39	7.0	7.8	130172
137.92	46.21	6.0	7.5	110143
137.92	42.81	6.5	6.3	110172
137.92	43.18	6.3	7.4	110153

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 860.11 MB ERROR 7.1 PER CENT

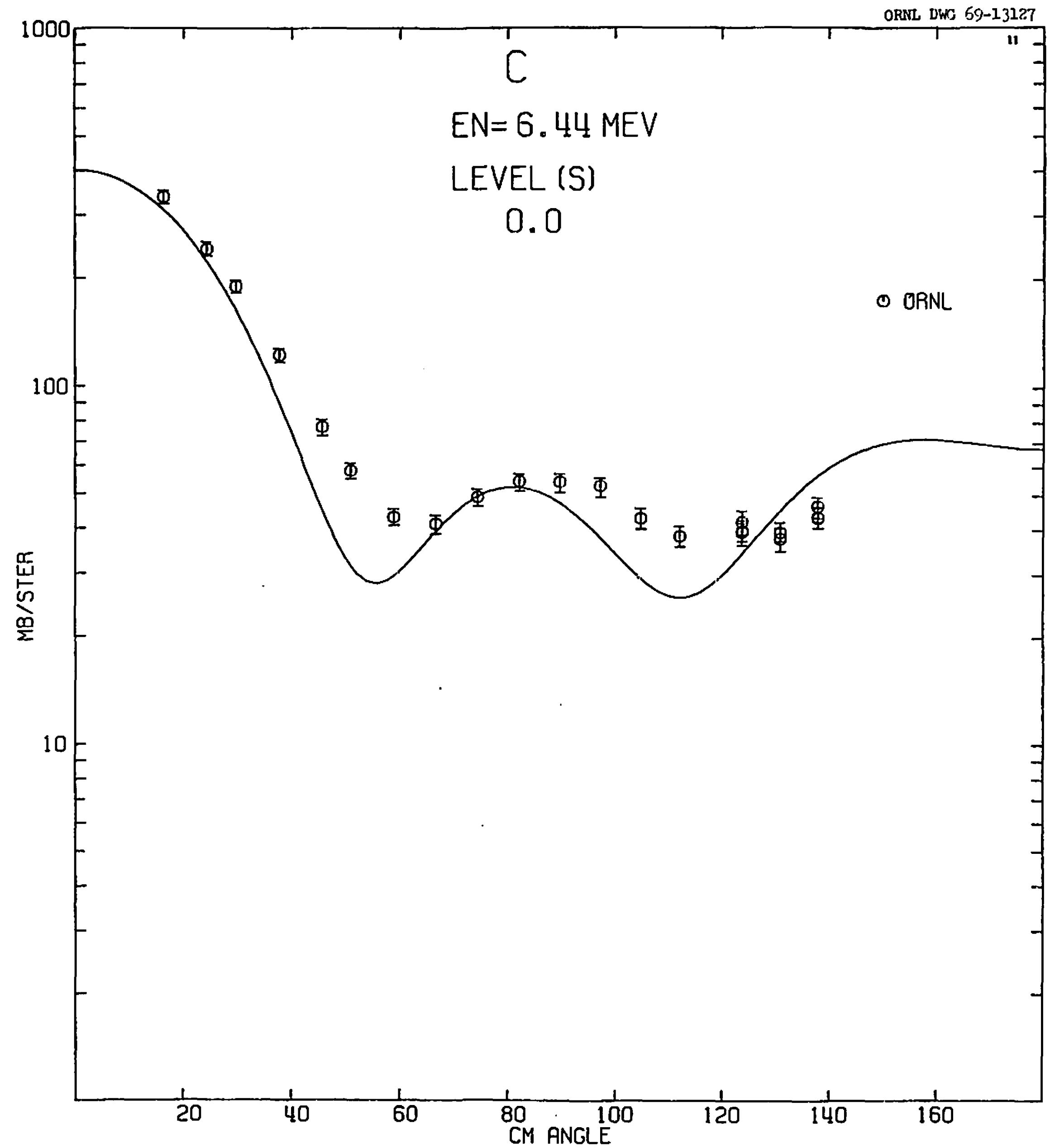

ORNL DWG 69-13127
C
EN= 6.44 MEV
LEVEL (S)
0.0
ORNL
MB/STER
1000
100
10
20
40
60
80
100
120
140
160
CM ANGLE

Figure 9

Table 10

SCATTERING OF 6.44 +OR- .07 MEV NEUTRONS FROM

LEVEL(S) 4.430 MEV KEY(21) 22 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
17.47	23.56	22.2	22.9	150490
26.16	22.36	20.8	14.4	130490
31.90	20.29	8.6	8.6	150189
40.49	21.01	8.3	8.5	130189
48.96	24.08	8.3	9.6	110189
54.56	24.67	8.6	8.3	150175
62.85	22.85	8.9	9.4	130175
70.98	20.17	9.3	9.8	110175
79.02	18.88	10.8	10.9	150113
86.85	17.28	11.2	10.9	130113
94.56	14.92	12.6	12.5	110113
102.08	17.80	14.5	14.4	150128
109.45	19.85	15.3	14.7	130128
116.64	18.83	16.2	16.6	110128
127.83	23.39	22.7	22.2	150143
127.84	23.78	22.6	22.3	150172
127.85	24.36	23.3	23.2	150153
134.45	25.02	26.5	25.8	130143
134.65	27.30	26.1	26.0	130172
141.31	24.64	28.7	29.0	110153
141.32	24.31	28.9	29.0	110143
141.33	25.19	28.9	29.1	110172

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 261.57 MB ERROR 7.8 PER CENT

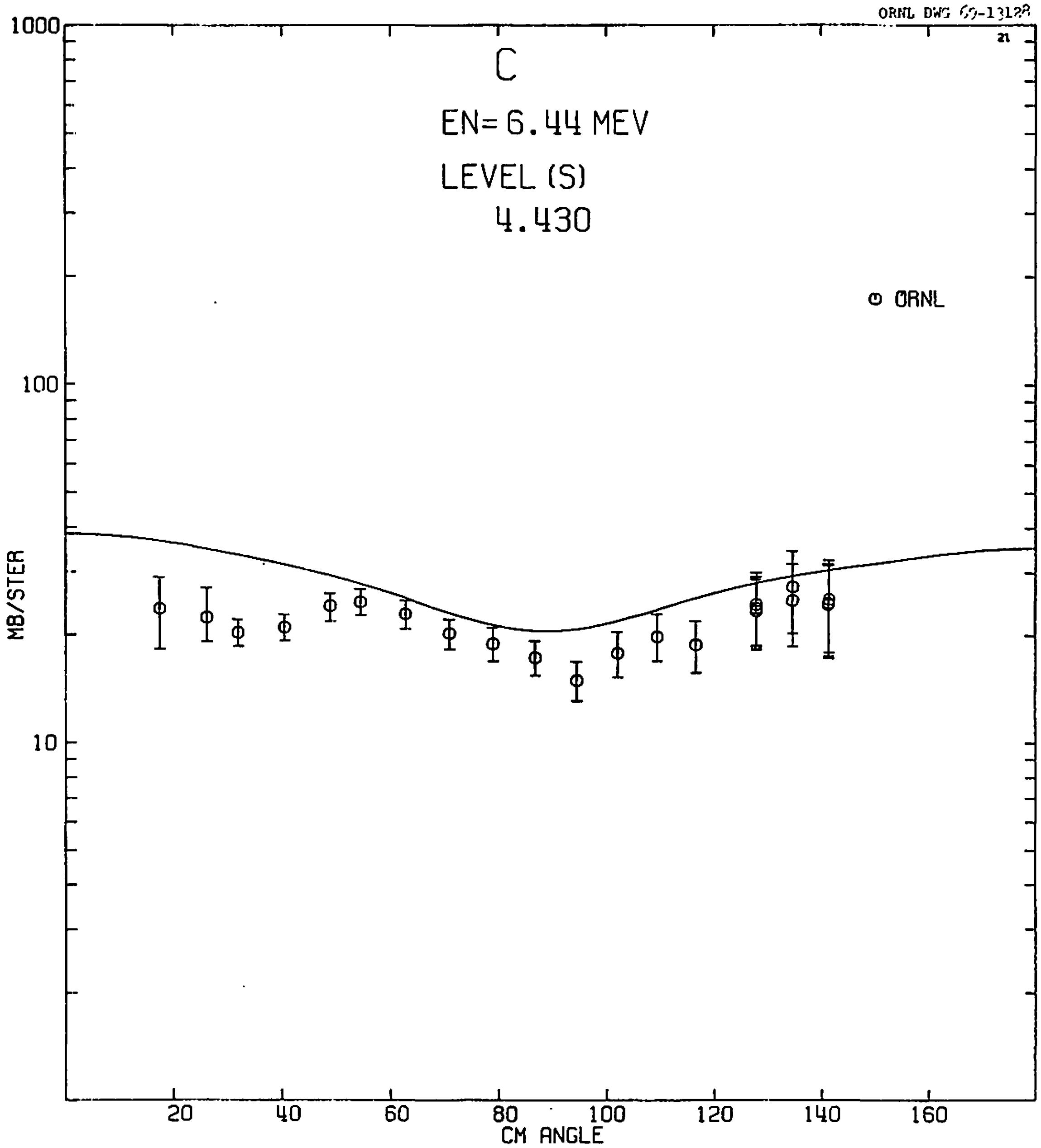

ORNL DWG 69-13128
C
EN= 6.44 MEV
LEVEL (S)
4.430
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 10

Table 11

SCATTERING ØF 7.03 +ØR= .06 MEV NEUTRØNS FRØM

LEVEL(S) 0 MEV KEY(11) 21 ANGLES

ANGLE CM	X-SEC. MB/STR	ERRØR(0/0) +	ERRØR(0/0) -	RUN
MULTIPLE SCATTERING CØRRECTIØN DØNE				
29.71	88.33	4.6	4.8	150414
29.71	88.44	4.5	4.8	150435
37.74	70.16	4.3	5.0	130414
37.75	76.99	4.4	4.8	130435
41.48	71.30	4.8	4.4	150437
45.74	62.03	4.5	4.6	110414
45.74	64.27	4.4	4.8	110435
49.45	57.05	4.6	4.8	130437
51.03	58.46	4.3	4.5	150428
57.35	50.43	4.8	5.0	110437
58.92	48.45	4.4	4.5	130428
66.75	41.79	4.5	5.0	110428
74.51	41.80	4.9	5.5	150401
82.19	43.39	4.9	5.4	130401
89.79	47.73	5.2	5.2	110401
97.29	51.55	4.9	4.9	150439
104.72	50.89	4.9	5.3	130439
112.07	46.68	5.0	5.2	110439
123.67	39.48	4.9	5.7	150421
130.82	29.01	5.6	5.4	130421
137.91	22.76	5.5	6.0	110421

AVERAGE X-SEC 0 MB/STR 0 NØTE

INTEGRATED X-SEC 601.44 MB ERRØR 7.1 PER CENT

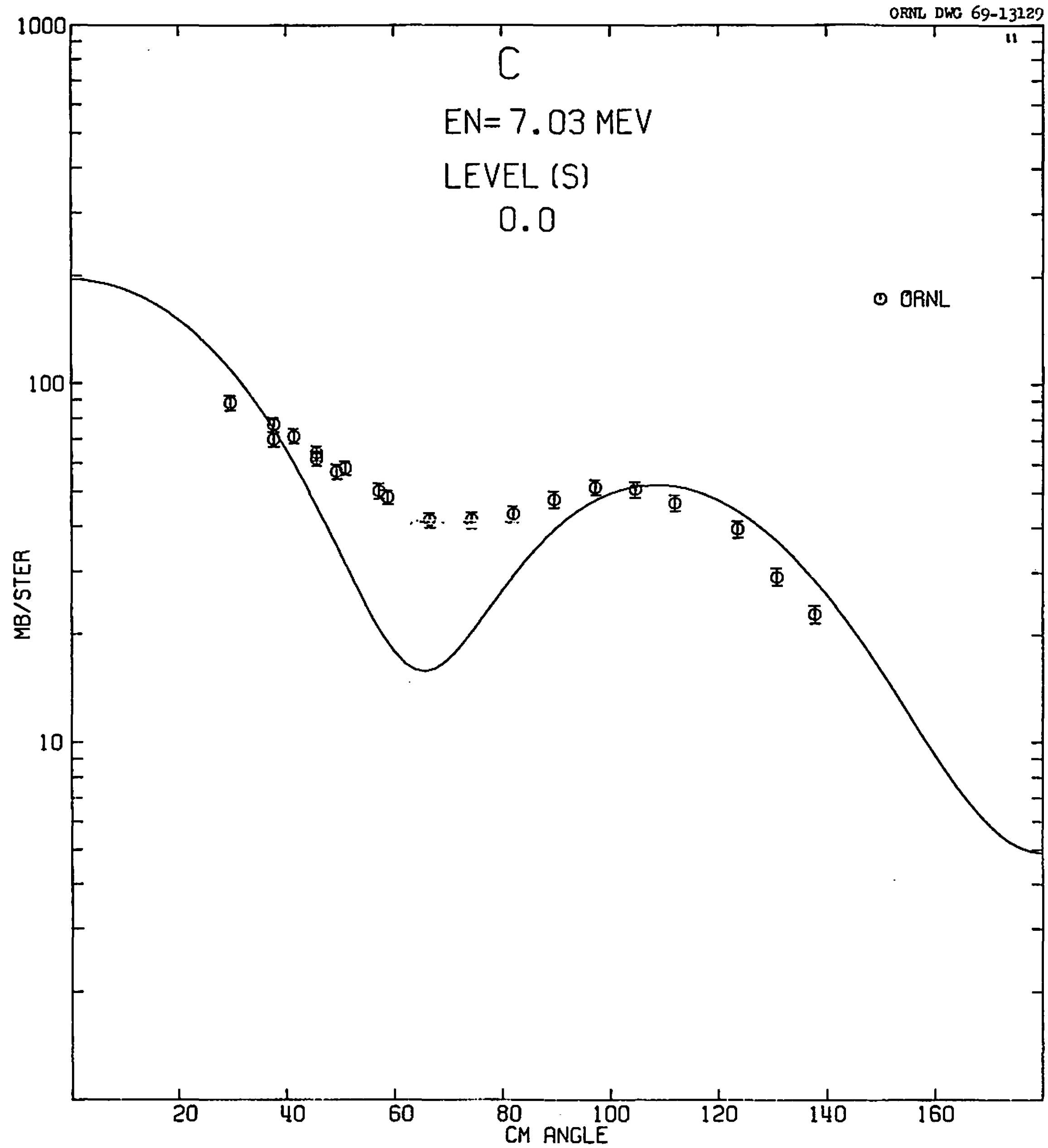

ORNL DWG 69-13129
C
EN= 7.03 MEV
LEVEL (S)
0.0
ORNL
MB/STER
CM ANGLE
1000
100
10
20
40
60
80
100
120
140
160

Figure 11

Table 12

SCATTERING OF 7.03 +OR- .06 MEV NEUTRONS FROM

LEVEL(S) 4.430 MEV KEY(21) 21 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
MULTIPLE SCATTERING CORRECTION DONE				
31.44	13.64	8.0	8.9	150414
31.44	14.65	8.3	8.9	150435
39.90	14.39	8.2	8.5	130435
39.90	13.62	7.5	9.2	130414
43.81	16.24	7.3	7.7	150437
48.27	15.12	7.3	7.8	110414
48.29	15.48	7.4	7.7	110435
52.15	14.76	7.5	8.0	130437
53.81	15.52	6.9	7.0	150428
60.37	13.39	7.7	8.7	110437
62.01	14.00	7.0	7.5	130428
70.09	11.68	7.6	8.9	110428
78.04	10.66	8.0	8.9	150401
85.84	9.17	8.2	9.2	130401
93.55	9.10	7.4	8.2	110401
101.05	9.11	9.5	9.8	150439
108.44	10.30	9.3	9.6	130439
115.68	11.77	9.6	10.0	110439
126.94	13.93	9.6	9.8	150421
133.83	15.13	9.8	10.0	130421
140.60	14.87	10.4	11.0	110421

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 166.60 MB ERROR 7.3 PER CENT

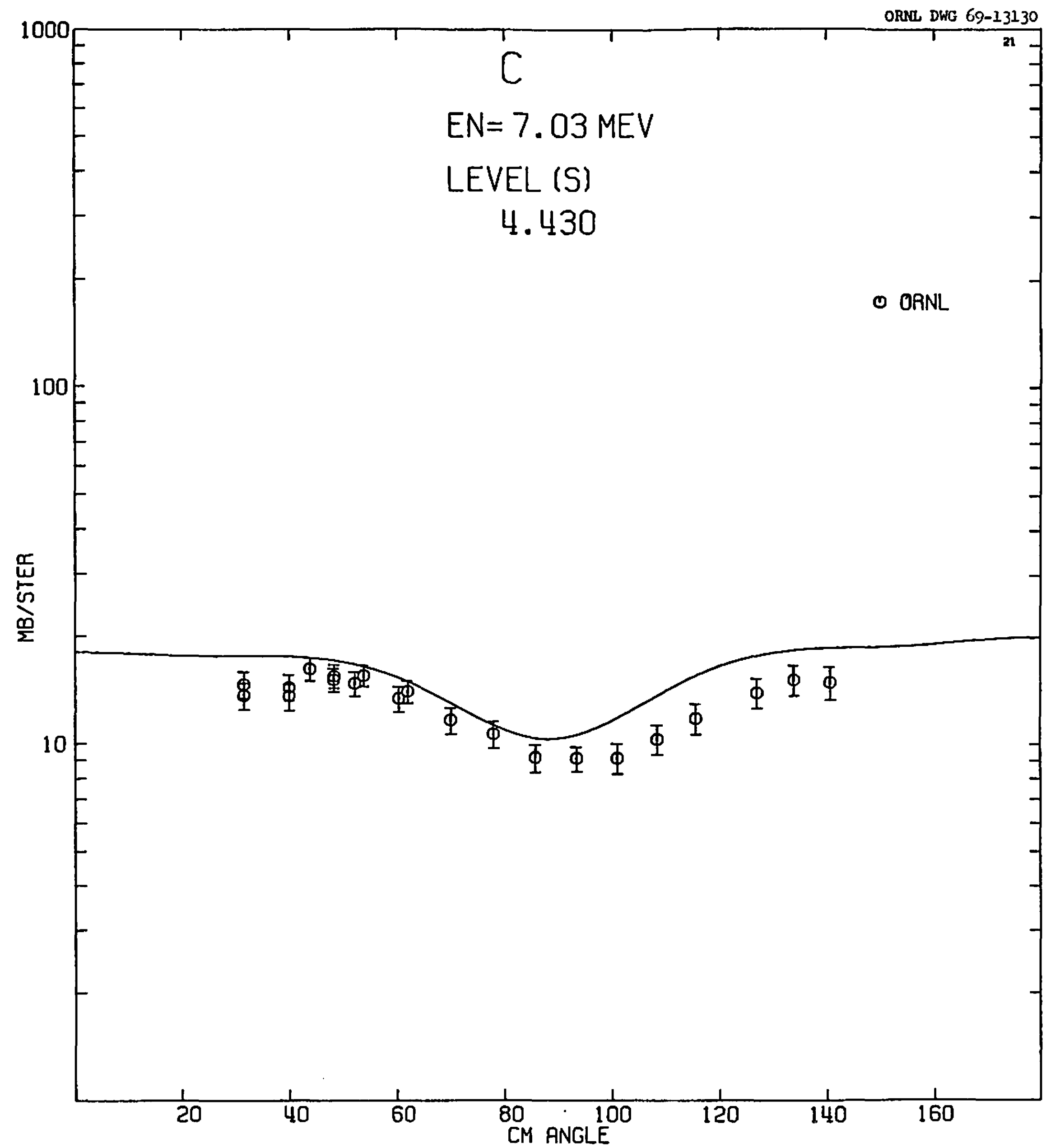

ORNL DWG 69-13130
21
C
EN= 7.03 MEV
LEVEL (S)
4.430
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 12

Table 13

SCATTERING OF 7.54 +OR- .06 MEV NEUTRONS FROM

LEVEL(S) 0 MEV KEY(11) 26 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(O/O) +	ERROR(O/O) -	RUN
16.24	558.22	3.9	6.2	150514
24.33	419.27	4.3	4.2	130514
29.71	351.56	4.2	4.2	150073
37.75	247.63	4.4	4.5	130073
45.74	162.31	4.5	5.4	110073
51.03	123.28	4.7	5.3	150067
51.04	113.38	5.2	5.1	150022
58.92	55.59	6.3	6.5	130022
58.93	58.41	5.7	6.1	130067
66.75	22.47	9.4	9.8	110022
66.75	23.75	8.7	9.1	110067
74.50	5.42	21.7	20.0	150052
82.17	3.05	33.1	42.2	130052
89.79	8.09	17.5	17.1	110052
97.28	20.16	9.5	13.1	150101
97.29	23.15	9.2	10.2	150035
104.72	34.85	7.2	8.8	130101
104.72	38.29	7.1	7.3	130035
112.07	50.89	6.2	6.5	110101
112.08	55.64	6.1	6.9	110035
123.67	80.45	6.1	6.4	150086
123.69	88.00	5.4	6.6	150042
130.83	98.37	5.7	7.1	130086
131.31	95.49	5.5	5.6	130042
137.92	123.15	5.2	6.7	110086
137.92	116.17	5.2	5.3	110042

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1304.77 MB ERROR 7.1 PER CENT

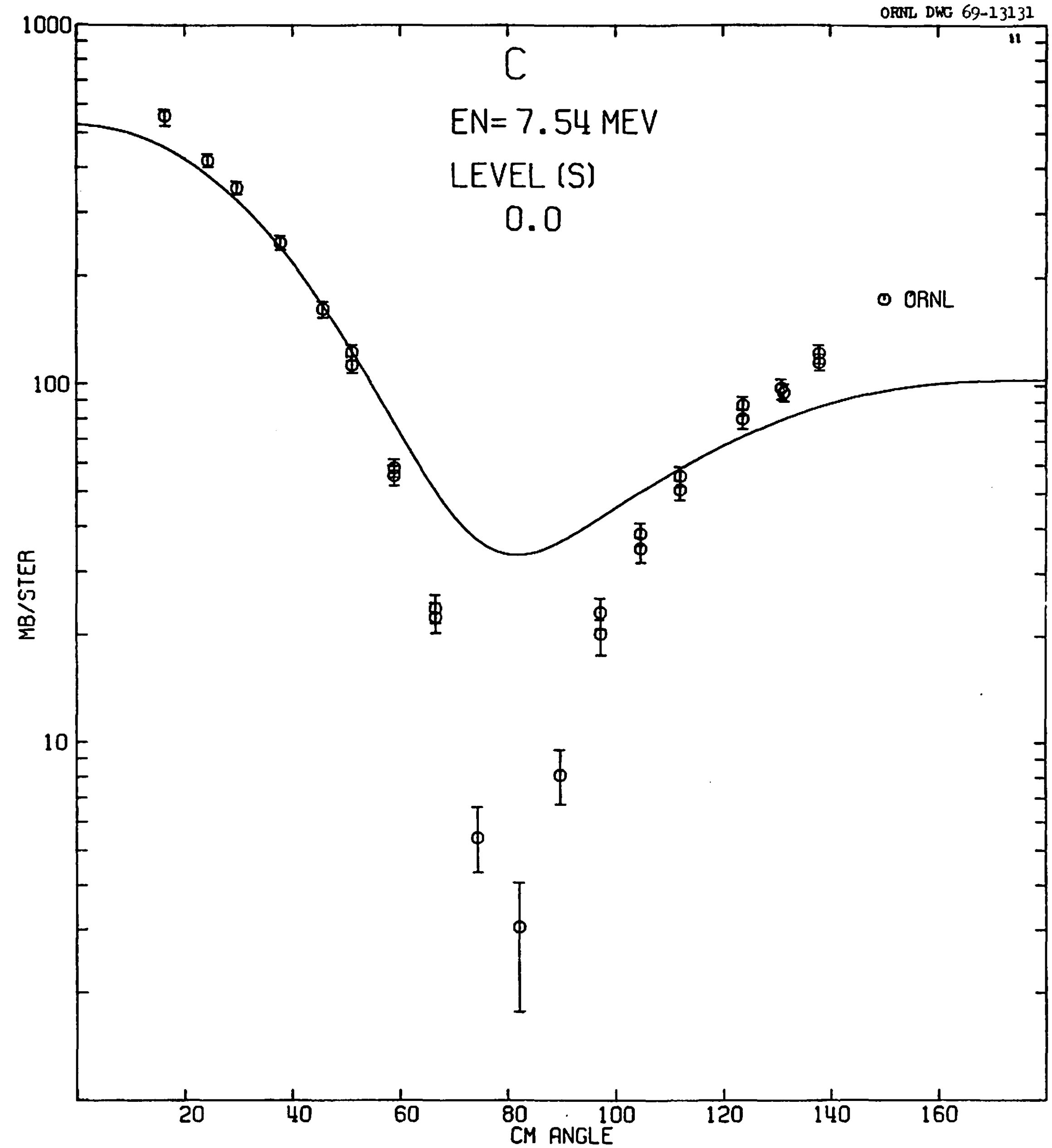

ORNL DWG 69-13131
C
EN= 7.54 MEV
LEVEL (S)
0.0
ORNL
MB/STER
1000
100
10
20
40
60
80
100
120
140
160
CM ANGLE

Figure 13

Table 14

SCATTERING OF 7.54 +OR- .06 MEV NEUTRONS FROM C1

LEVEL(S) 4.430 MEV KEY(21) 26 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(O/O) +	ERROR(O/O) -	RUN
17.06	10.89	23.2	26.4	150514
25.55	13.53	23.8	20.4	130514
31.18	14.45	8.6	10.0	150073
39.57	16.39	6.6	8.5	130073
47.88	17.07	7.6	7.5	110073
53.38	20.82	6.9	7.1	150067
53.39	21.70	8.0	6.8	150022
61.53	22.68	6.6	6.8	130067
61.53	21.25	7.4	6.9	130022
69.58	23.09	7.0	7.0	110022
69.59	24.97	6.9	7.2	110067
77.51	29.34	7.0	6.7	150052
85.31	29.84	7.1	7.0	130052
92.98	30.45	7.0	7.1	110052
100.48	31.80	7.1	7.9	150101
100.49	29.19	6.8	7.8	150035
107.87	29.11	7.7	7.8	130101
107.88	28.32	7.6	7.4	130035
115.12	26.55	8.0	8.3	110101
115.13	26.55	7.7	7.4	110035
126.45	27.01	8.1	9.0	150086
126.46	27.49	8.2	8.3	150042
133.37	25.40	9.3	10.4	130086
133.83	26.33	8.3	7.9	130042
140.18	25.30	10.5	8.9	110086
140.20	26.15	8.2	8.5	110042

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 302.40 MB ERROR 7.2 PER CENT

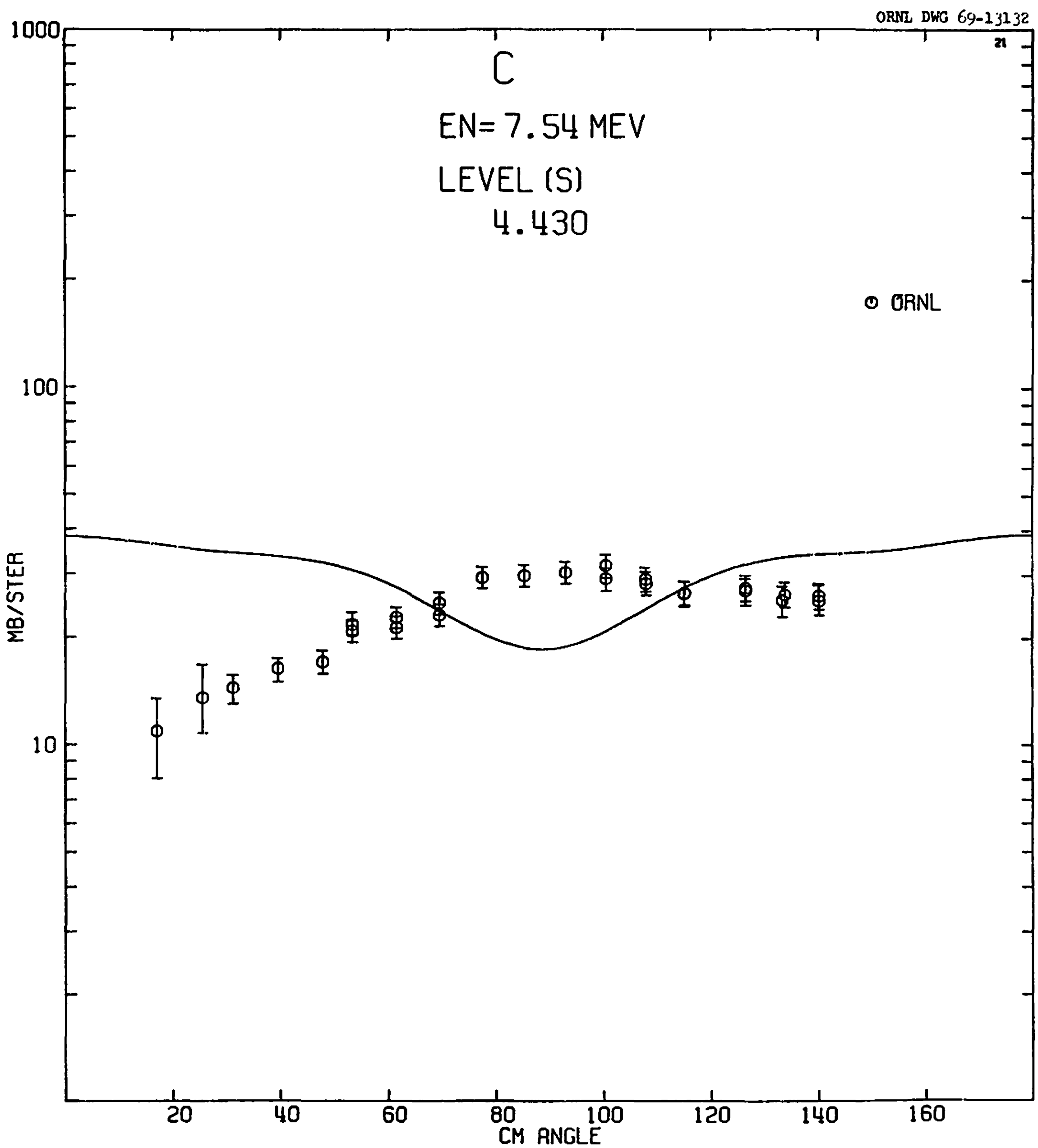

ORNL DWG 69-13132
C
EN= 7.54 MEV
LEVEL (S)
4.430
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 14

Table 15

SCATTERING OF 7.60 +OR- .10 MEV NEUTRONS FROM C

LEVEL(S) 0 MEV KEY(11) 21 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN

MULTIPLE SCATTERING CORRECTION DONE

23.80	363.99	4.0	5.8	150157
29.18	299.52	4.3	5.9	150165
34.54	237.19	4.2	5.4	150147
35.61	224.33	4.4	5.0	130152
40.95	173.62	4.3	5.8	130169
46.27	132.23	4.5	5.7	130147
50.51	96.24	4.6	5.4	150120
56.30	58.35	4.9	5.5	110120
62.07	33.82	6.1	5.8	130120
66.24	23.25	5.9	7.7	150126
71.93	10.22	9.6	9.8	110126
74.69	9.91	8.9	12.2	150132
77.59	6.91	12.1	12.4	130126
80.27	4.58	17.4	19.9	110132
85.81	8.43	12.5	12.9	130132
86.77	10.68	10.3	12.1	150138
92.31	14.64	8.9	10.7	110138
97.81	29.24	6.1	8.3	130138
99.79	28.69	6.3	7.6	150142
110.62	57.78	4.8	7.2	130142
122.25	76.37	4.2	5.0	140098

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1075.65 MB ERROR 7.2 PER CENT

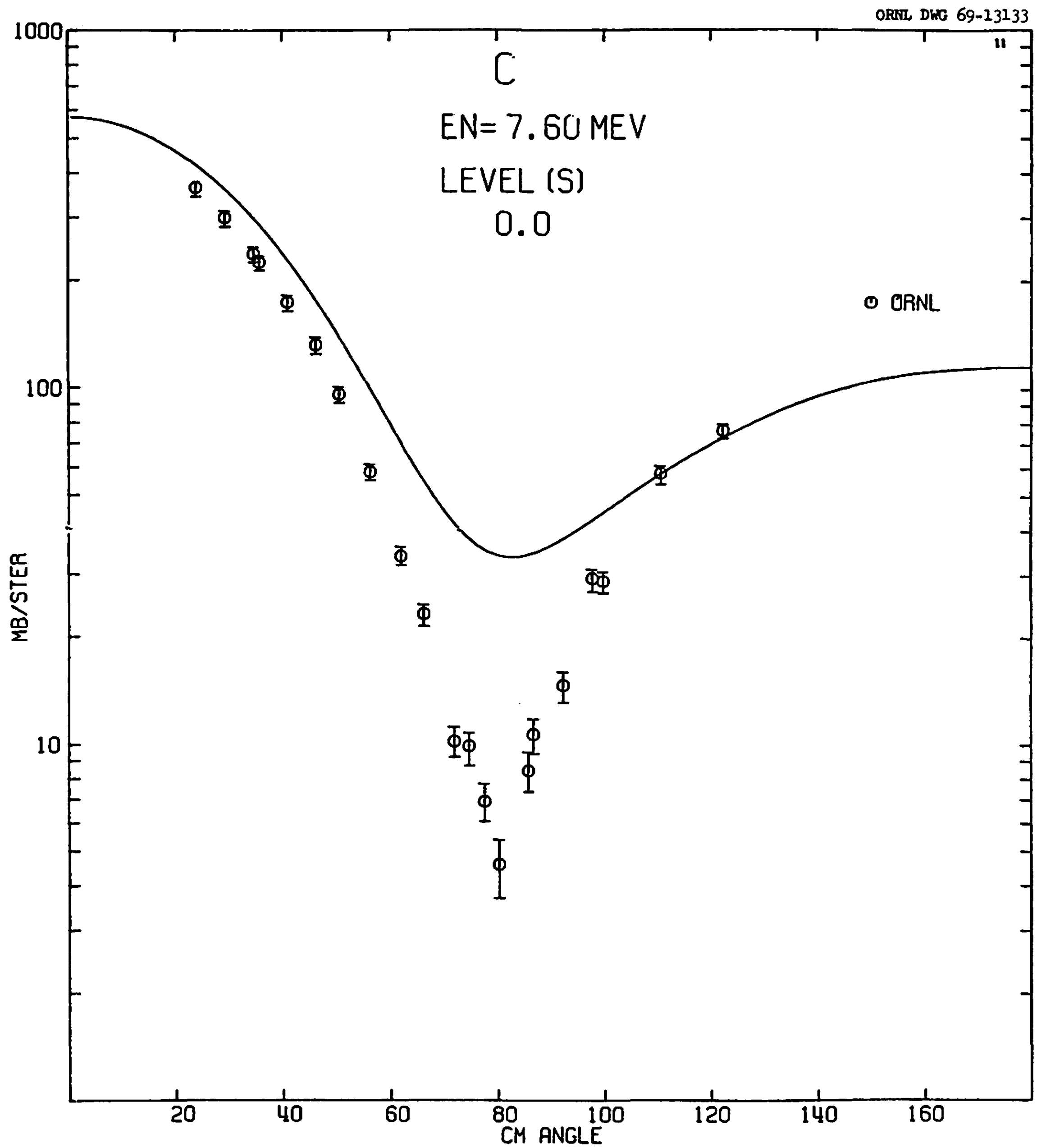

ORNL DWG 69-13133
C
EN= 7.60 MEV
LEVEL (S)
0.0
ORNL
MB/STER
CM ANGLE
1000
100
10
20
40
60
80
100
120
140
160

Figure 15

Table 16

SCATTERING OF 7.60 +OR- .10 MEV NEUTRONS FROM C

LEVEL(S) 4.430 MEV KEY(21) 23 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
25.00	10.87	22.0	8.9	150157
30.60	10.72	9.5	11.1	150165
36.24	13.56	7.5	13.2	150147
37.35	13.37	14.3	8.5	130152
42.32	13.16	8.5	8.5	110147
42.88	13.43	8.3	10.3	130169
48.43	16.24	12.8	8.9	130147
52.80	16.52	9.5	6.6	150120
58.78	18.19	6.1	8.1	150098
58.79	19.32	8.3	4.7	110120
64.72	21.33	9.2	4.9	130120
69.00	20.61	10.2	5.9	150126
74.82	23.00	5.7	5.2	110126
80.58	25.50	8.7	6.2	130126
84.72	23.93	10.0	6.0	150132
89.86	27.05	9.1	6.3	150138
90.36	26.02	9.5	6.1	110132
95.42	27.90	8.6	7.0	110138
95.92	27.98	9.5	6.5	130132
100.91	28.79	8.5	6.4	130138
102.89	27.09	9.7	6.5	150142
113.61	26.28	10.3	6.7	130142
125.05	26.79	6.8	10.0	140098

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 273.47 MB ERROR 8.3 PER CENT

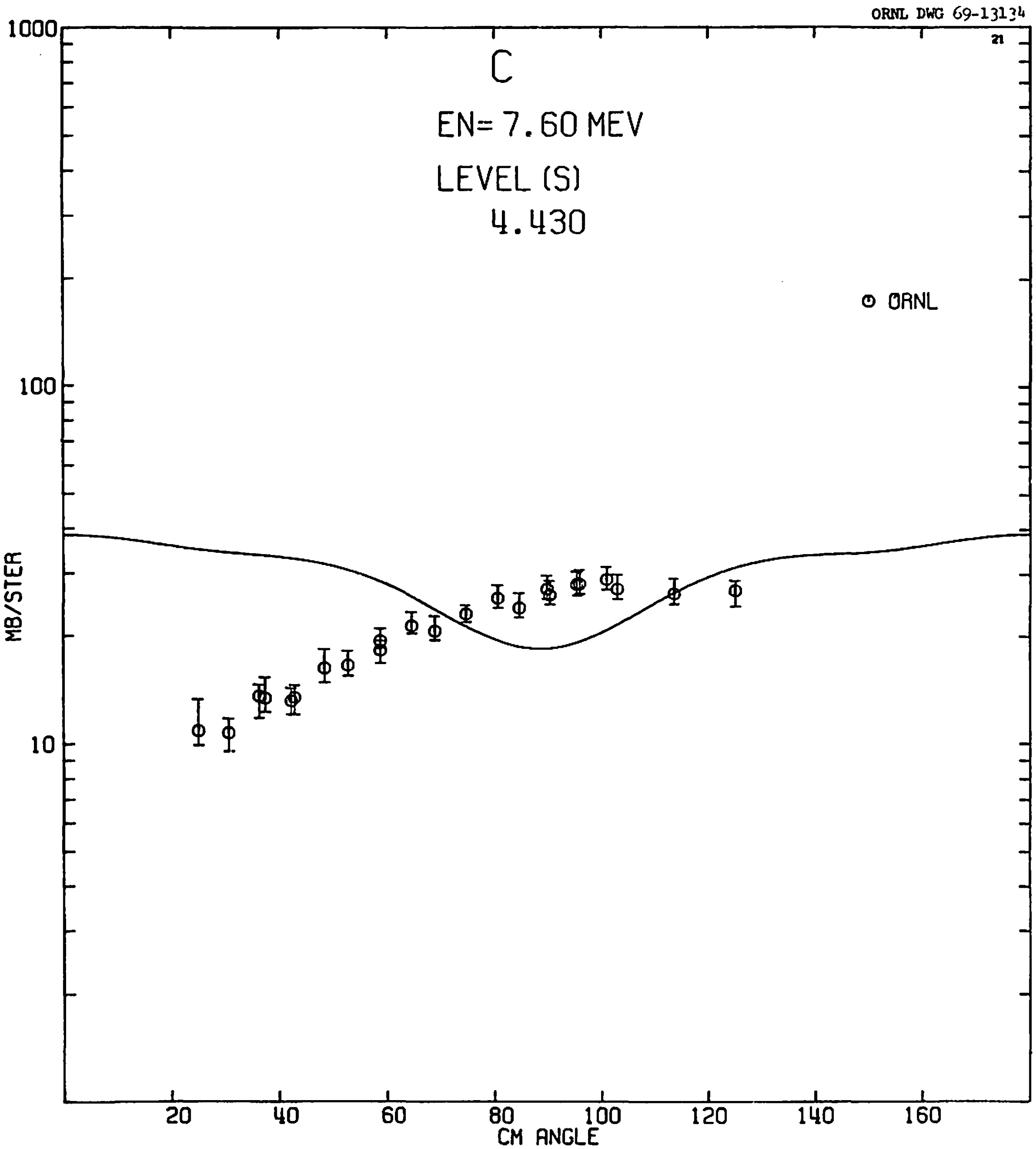

ORNL DWG 69-13134
21
C
EN= 7.60 MEV
LEVEL (S)
4.430
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 16

Table 17

SCATTERING OF 8.04 +OR- .05 MEV NEUTRONS FROM

LEVEL(S) 0 MEV KEY(11) 15 ANGLES

ANGLE CM	X-SEC, MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
	MULTIPLE SCATTERING CORRECTION DONE			
29.72	443.52	4.0	4.2	150386
37.75	280.98	4.3	4.5	130386
45.74	163.67	4.5	5.3	110386
51.04	108.09	4.8	5.1	150357
58.93	40.12	7.4	6.9	130357
66.75	11.27	13.0	14.1	110357
74.51	6.50	17.3	21.7	150372
82.17	12.13	13.4	13.9	130372
89.79	19.60	7.3	8.8	150372
97.30	25.78	7.1	9.1	150392
104.74	26.05	9.2	8.0	130392
112.09	25.81	7.9	9.2	110392
123.69	37.62	7.0	9.5	150365
130.83	42.74	6.7	7.7	130365
137.93	57.92	5.7	7.3	110365

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 1202.80 MB ERROR 7.6 PER CENT

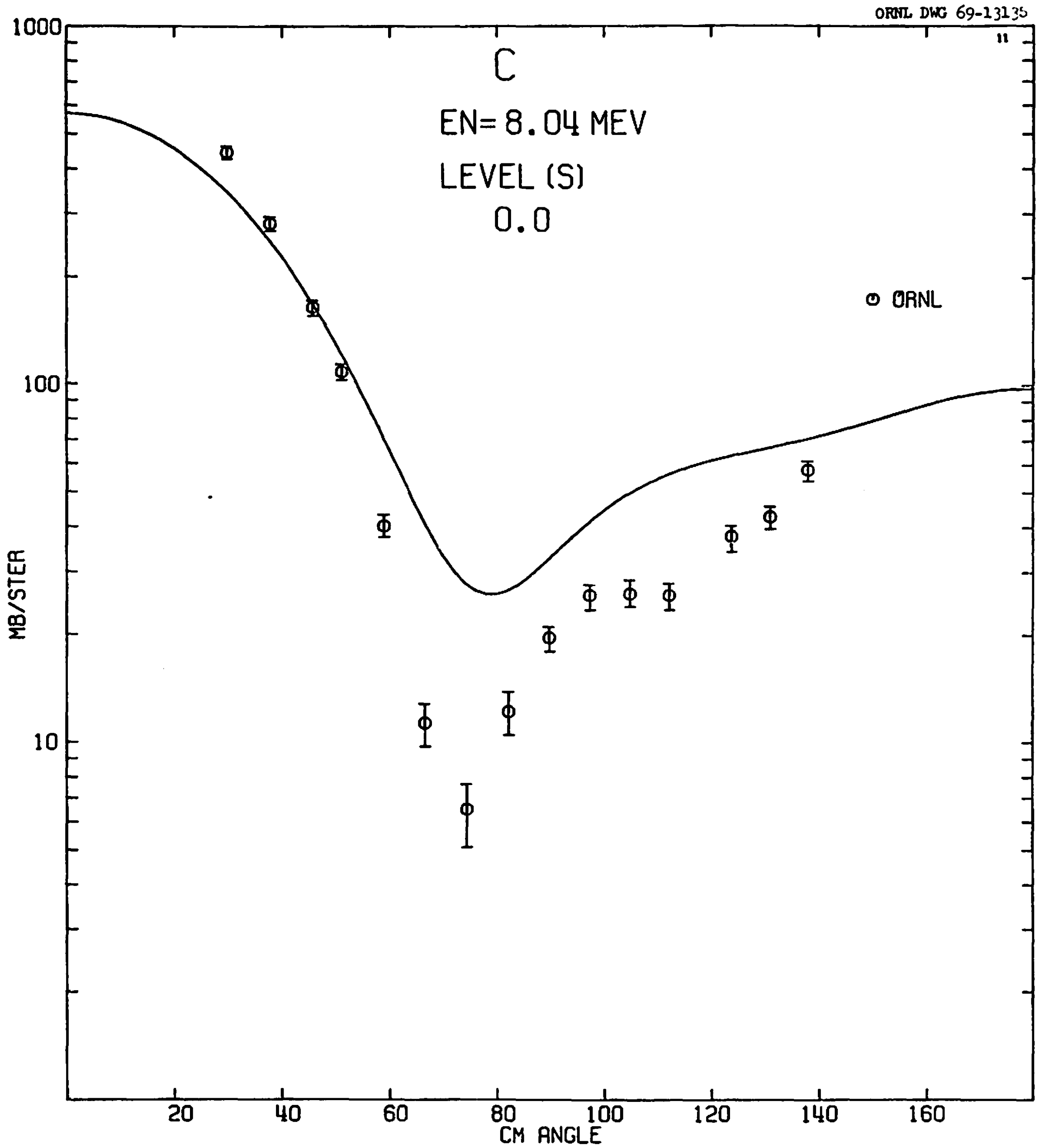

ORNL DWG 69-13135
C
EN= 8.04 MEV
LEVEL (S)
0.0
ORNL
MB/STER
1000
100
10
20
40
60
80
100
120
140
160
CM ANGLE

Figure 17

Table 18

SCATTERING OF 8.04 +OR= .05 MEV NEUTRONS FROM

LEVEL(S) 4.430 MEV KEY(21) 15 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X=SEC, MB/STR	ERROR(0/0) +	ERROR(0/0) =	RUN
31.00	30.03	6.5	7.0	150386
39.34	25.52	6.9	8.0	130386
47.62	22.10	6.6	7.9	110386
53.08	24.01	5.7	6.0	150357
61.20	20.61	5.6	7.2	130357
69.22	19.44	6.8	6.5	110357
77.12	19.39	6.4	7.0	150372
84.90	22.09	5.5	6.1	130372
92.55	25.62	5.3	5.9	150372
100.08	29.80	6.0	7.0	150392
107.49	35.45	6.1	7.7	130392
114.73	38.28	6.5	6.5	110392
126.10	45.14	6.9	7.2	150365
133.05	49.24	6.8	7.9	130365
139.90	48.34	6.8	6.7	110365

AVERAGE X=SEC 0 MB/STR 0 NOTE

INTEGRATED X=SEC 409.02 MB ERROR 7.2 PER CENT

ORNL DWG 69-13136

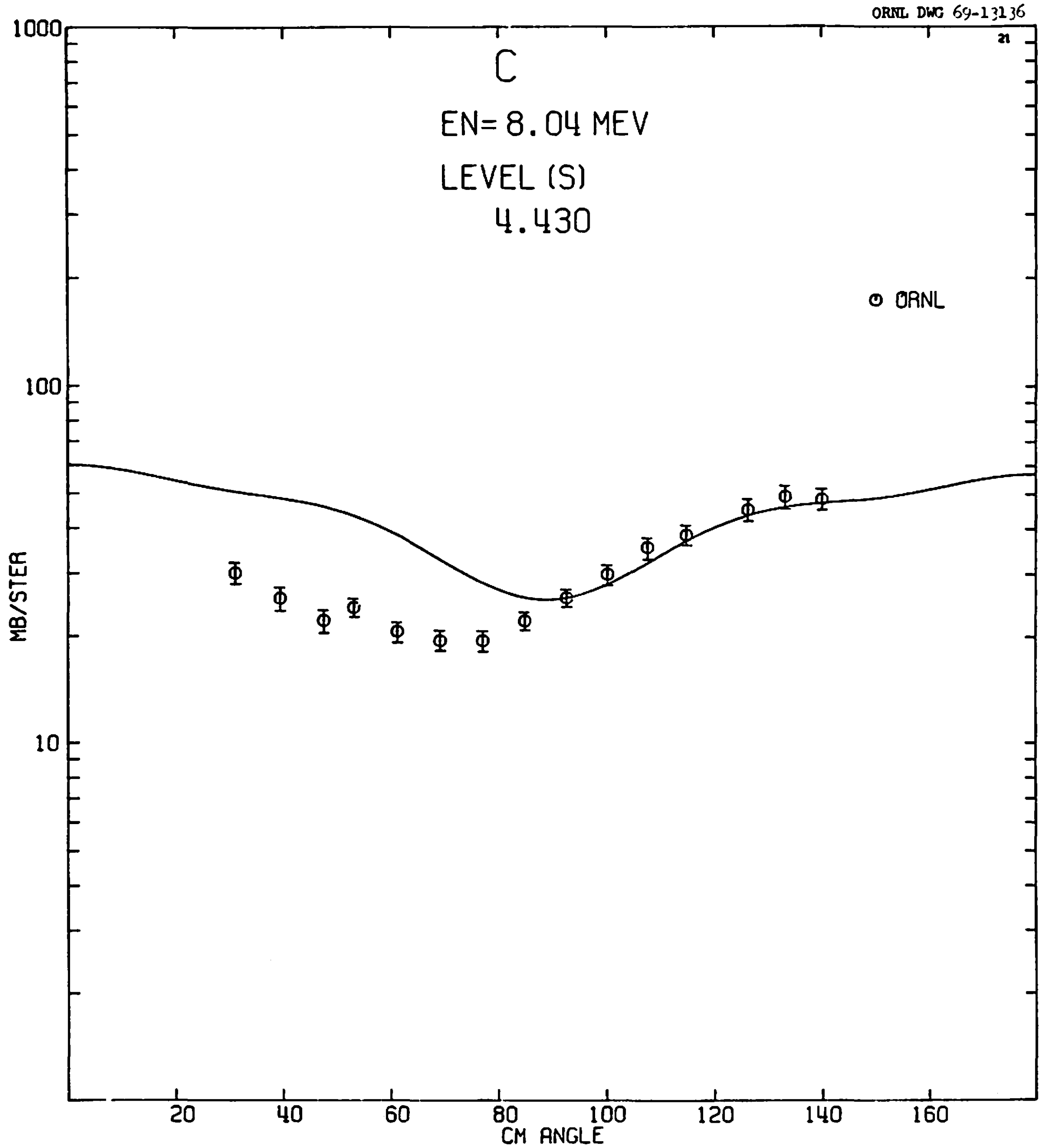


Figure 18

Table 19

SCATTERING OF 8.50 +OR- .08 MEV NEUTRONS FROM Si

LEVEL(S) 0 MEV KEY(11) 32 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(O/O) +	-	RUN
MULTIPLE SCATTERING CORRECTION DONE				
24.88	289.11	4.0	6.9	130413
25.95	302.59	4.0	5.1	100275
30.26	234.43	4.0	5.7	130407
31.32	230.97	4.3	6.8	100250
35.61	176.51	4.2	6.5	130401
36.68	182.14	4.5	6.0	100241
40.95	127.30	4.3	7.5	130394
42.02	118.53	4.4	7.1	100134
45.21	93.37	4.0	6.6	150377
47.35	81.75	4.9	9.2	100258
51.03	51.93	4.4	7.5	110377
52.63	49.61	5.0	7.3	100147
56.84	26.51	5.1	8.5	130377
57.89	20.06	6.6	6.6	100216
61.03	12.94	6.6	12.0	150355
63.12	10.76	7.4	12.5	100150
66.77	5.14	10.6	23.3	110355
72.46	3.70	14.6	21.3	130355
73.48	5.63	12.9	11.5	100173
76.63	9.97	6.9	19.4	150357
82.20	17.71	5.9	18.2	110357
83.70	24.15	5.9	6.7	100182
87.76	27.71	5.2	9.4	130357
91.80	34.38	4.6	9.0	150364
93.79	40.23	5.3	5.9	100185
97.31	44.65	4.4	7.2	110364
102.76	46.61	4.3	6.3	130364
103.74	45.55	4.7	6.4	100199
106.70	46.48	4.3	7.4	150370
112.08	45.62	4.3	7.5	110370
117.42	43.96	4.4	7.6	130370
117.70	42.49	5.0	7.1	100203

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 838.57 MB ERROR 7.2 PER CENT

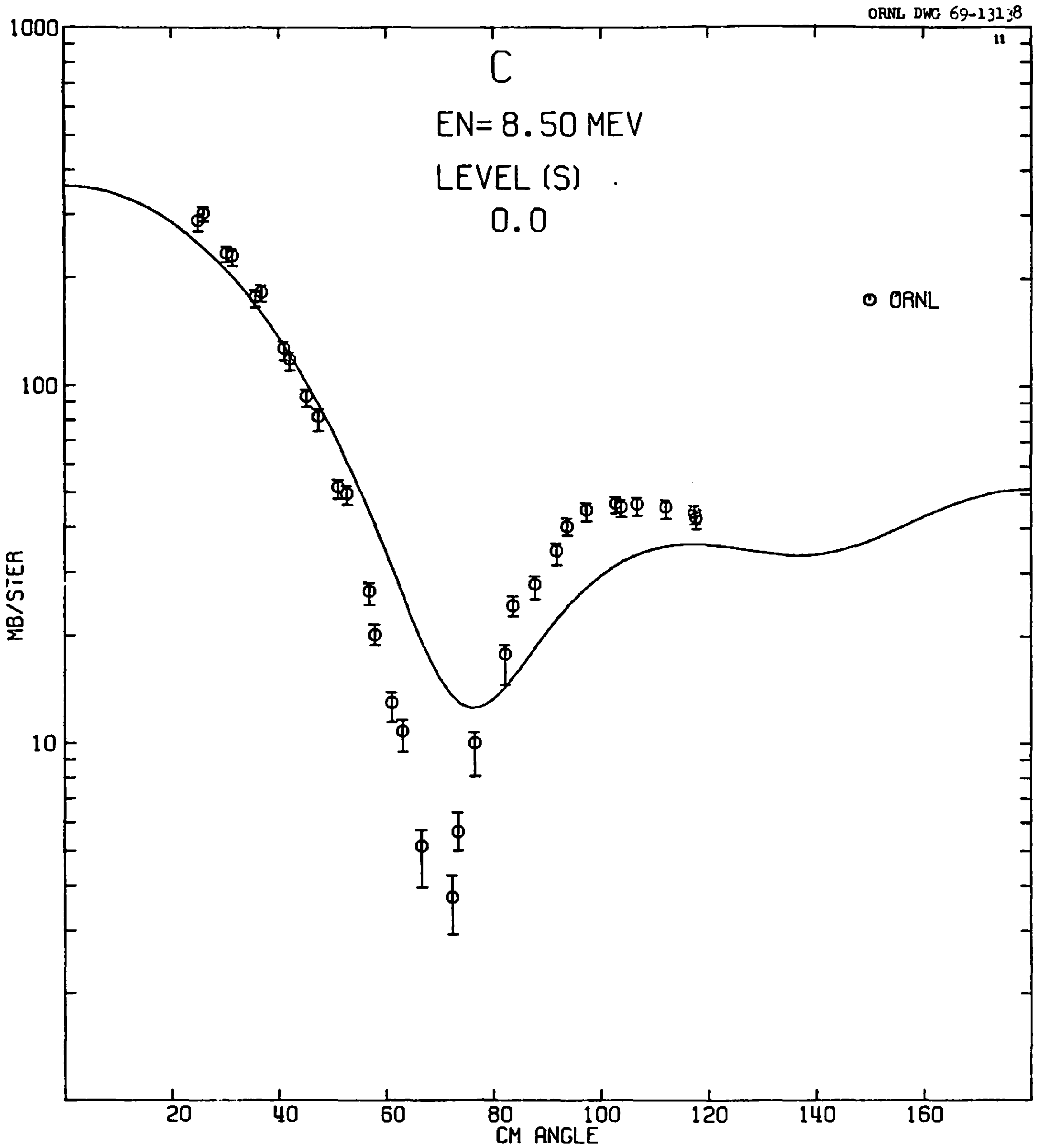

ORNL DWG 69-13138
C
EN= 8.50 MEV
LEVEL (S)
0.0
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 19

Table 20

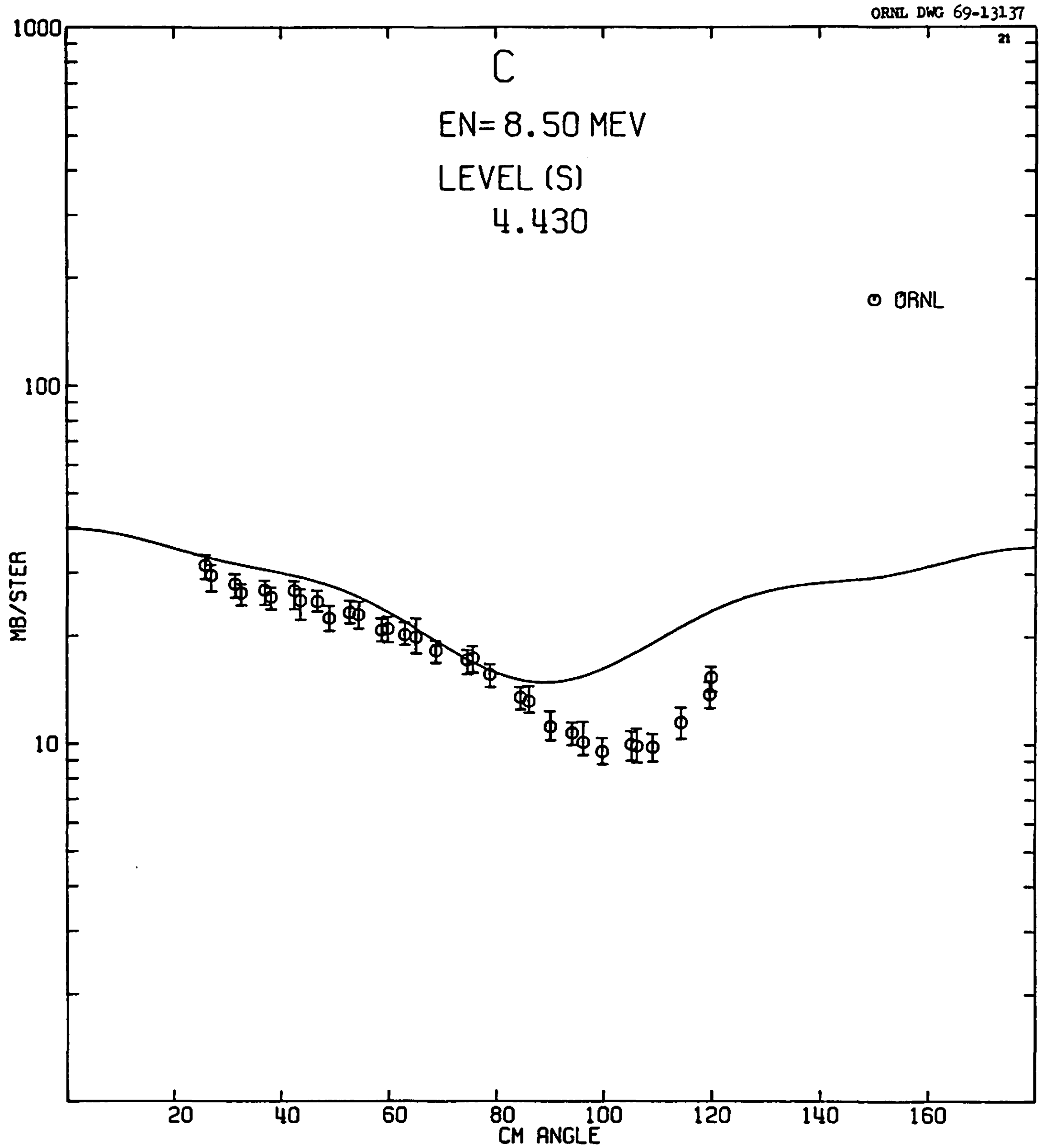
SCATTERING OF 8.50 +OR- .08 MEV NEUTRONS FROM C

LEVEL(S) 4.430 MEV KEY(21) 32 ANGLES

ANGLE CM	X-SEC. MB/STR	ERROR(O/O) +	ERROR(O/O) -	RUN
MULTIPLE SCATTERING CORRECTION DONE				
25.84	31.42	6.6	8.7	130413
26.95	29.40	7.0	10.0	100275
31.40	27.85	6.6	8.7	130407
32.52	26.30	5.5	7.8	100250
36.96	26.77	6.3	9.0	130401
38.07	25.61	6.2	7.6	100241
42.48	26.69	6.2	11.2	130394
43.58	25.05	7.5	11.7	100134
46.87	24.89	7.0	6.2	150377
49.06	22.39	8.0	8.2	100258
52.86	23.22	7.6	6.8	110377
54.49	22.89	8.4	8.7	100147
58.81	20.71	7.8	7.2	130377
59.89	20.93	7.8	8.8	100216
63.09	20.11	8.3	6.5	150355
65.25	19.79	12.9	9.9	100150
68.96	18.19	6.3	7.6	110355
74.76	17.16	6.4	8.8	130355
75.82	17.38	7.6	9.3	100173
78.92	15.63	6.7	8.0	150357
84.60	13.49	6.6	7.6	110357
86.15	13.15	10.1	7.2	100182
90.22	11.19	10.1	8.5	130357
94.26	10.75	6.9	7.6	150364
96.31	10.12	14.0	8.2	100185
99.78	9.53	9.0	8.1	110364
105.19	9.98	8.7	10.2	130364
106.21	9.86	11.9	10.2	100199
109.11	9.82	8.9	9.1	150370
114.44	11.52	9.9	10.2	110370
119.70	13.77	8.3	8.5	130370
119.98	15.39	6.9	8.8	100203

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 248.01 MB ERROR 7.5 PER CENT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LEVEL (S)
4.430
ORNL
MB/STER
1000
100
10
CM ANGLE
20
40
60
80
100
120
140
160

Figure 20

Table 21

SCATTERING OF 8.56 +OR- .05 MEV NEUTRONS FROM

LEVEL(S) 0 MEV KEY(11) 32 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
10.83	421.24	5.1	5.6	150551
16.24	385.11	5.3	6.7	150537
16.24	384.32	4.9	5.1	150556
24.34	324.21	4.7	5.3	130537
24.34	320.42	5.4	4.4	130556
29.72	253.61	3.9	4.4	150217
34.00	209.74	4.0	4.2	150324
37.75	165.63	4.0	4.8	130217
42.02	123.37	4.2	4.1	130324
45.73	86.02	4.9	5.1	150315
45.74	90.95	4.5	4.6	110217
49.98	60.77	4.9	4.9	110324
51.03	56.77	4.9	5.2	150270
53.67	36.53	7.0	7.4	130315
58.92	19.88	7.6	8.0	130270
61.54	11.06	11.8	11.6	110315
66.75	5.03	13.1	13.1	110270
74.50	5.28	20.2	25.0	150220
74.51	4.44	18.7	16.8	150227
82.18	15.37	6.5	10.3	130227
82.19	15.26	7.4	10.4	130220
89.77	30.79	5.3	6.3	110220
89.77	30.84	5.3	6.4	110227
97.29	46.09	5.3	5.3	150280
104.72	51.11	4.7	5.1	130280
112.07	52.70	4.8	5.1	110280
123.67	45.47	6.5	5.1	150235
123.67	42.80	5.2	5.2	150250
130.83	35.36	6.9	7.1	130250
130.83	36.33	5.0	6.7	130235
137.92	25.76	7.9	5.8	110235
137.92	25.50	6.9	8.8	110250

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 802.63 MB ERROR 7.1 PER CENT

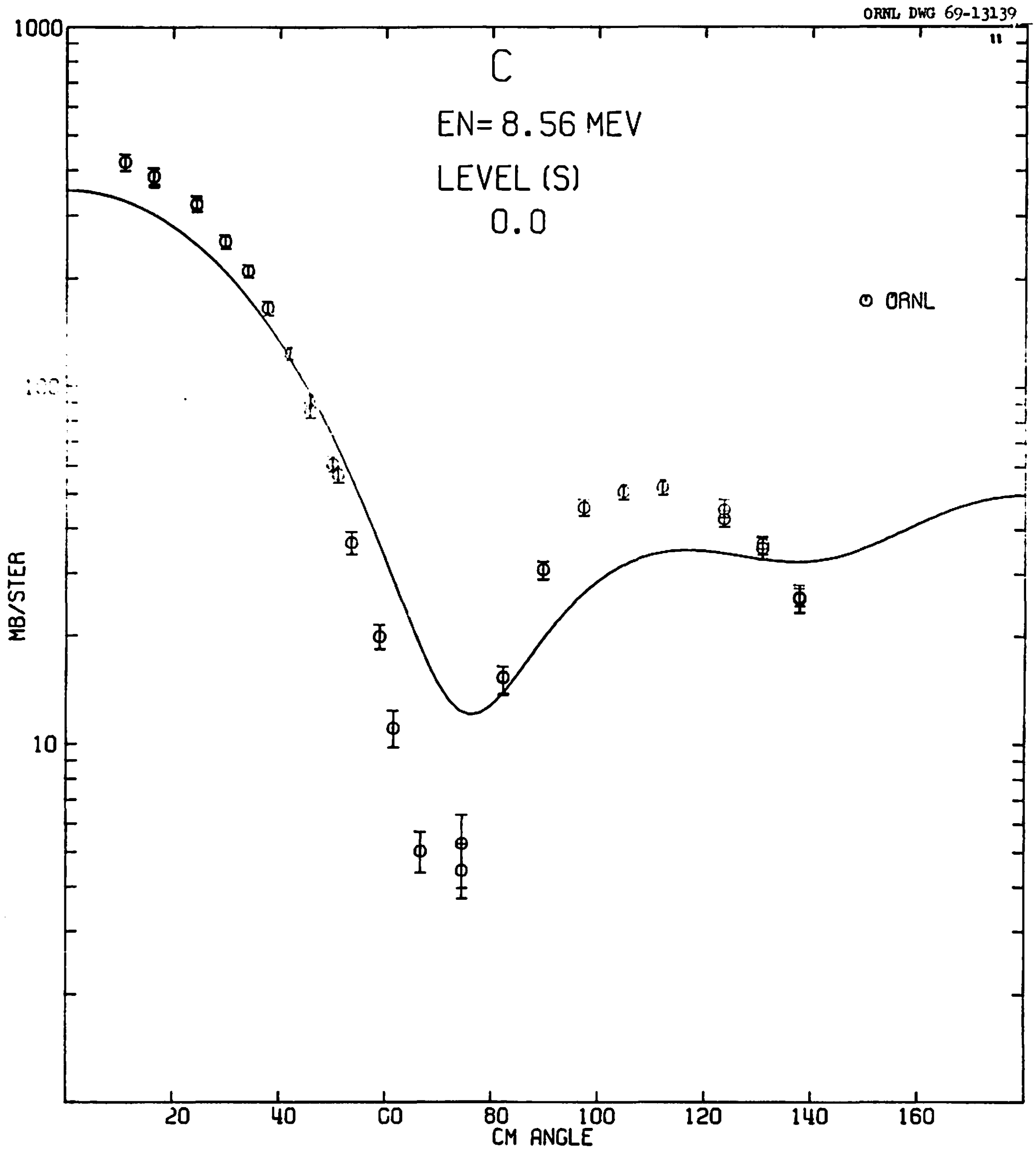

ORNL DWG 69-13139
C
EN= 8.56 MEV
LEVEL (S)
0.0
ORNL
1000
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 21

Table 22

SCATTERING OF 8.56 +OR- .05 MEV NEUTRONS FROM C

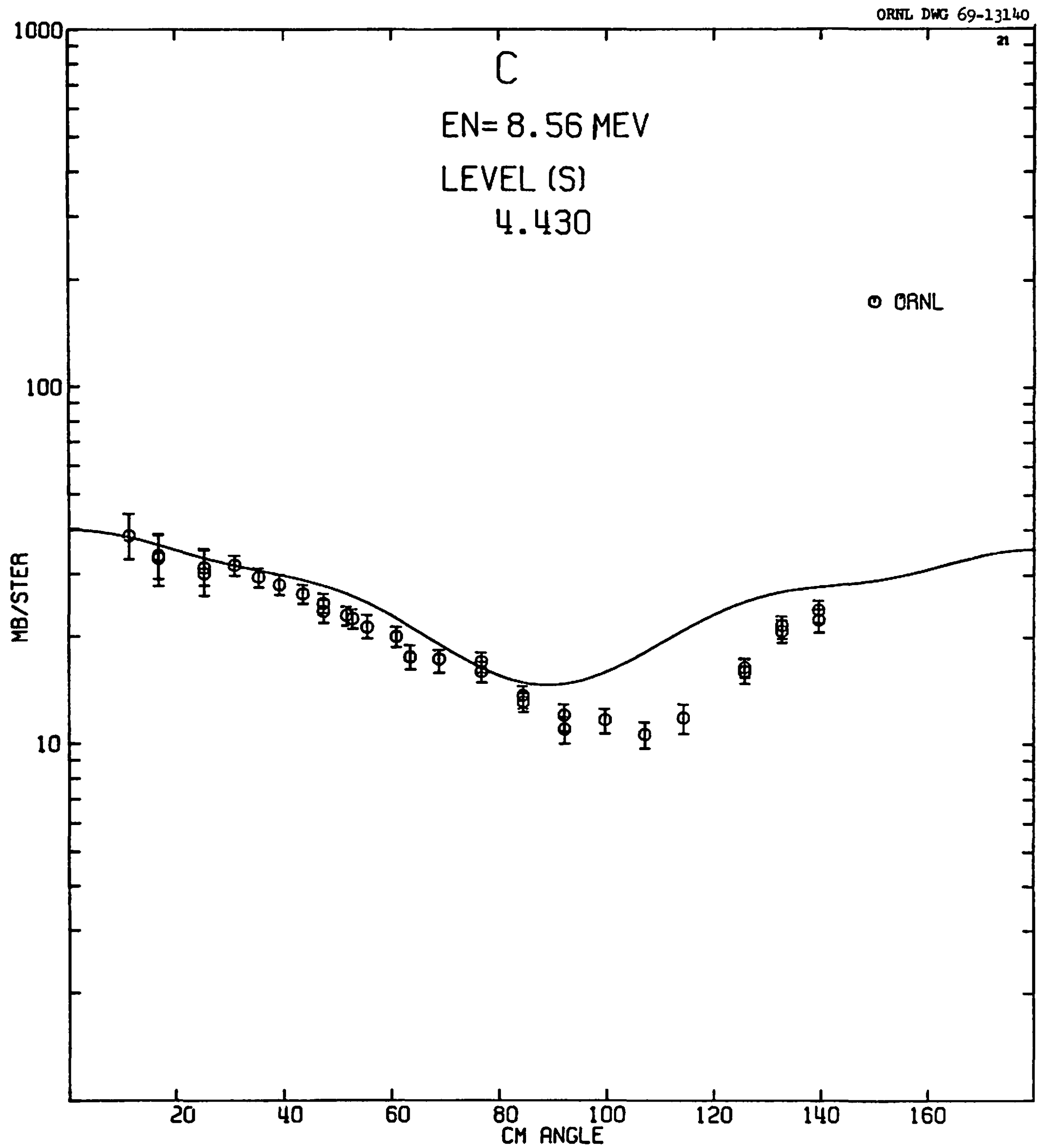
LEVEL(S) 4.430 MEV KEY(21) 32 ANGLES

MULTIPLE SCATTERING CORRECTION DONE

ANGLE CM	X-SEC. MB/STR	ERROR(0/0) +	ERROR(0/0) -	RUN
11.25	38.11	15.2	14.0	150551
16.87	33.62	13.8	14.1	150556
16.87	33.02	16.7	16.4	150537
25.27	31.13	12.9	11.0	130556
25.27	29.99	16.0	13.3	130537
30.84	31.65	6.1	6.8	150217
35.28	29.29	5.7	6.6	150324
39.15	27.91	6.9	6.5	130217
43.56	26.35	5.6	6.4	130324
47.38	24.75	6.3	6.3	110217
47.39	23.48	7.7	7.3	150315
51.76	22.90	5.6	6.5	110324
52.84	22.41	6.2	6.4	150270
55.55	21.21	8.1	7.1	130315
60.94	19.98	6.2	6.8	130270
63.62	17.51	7.8	7.9	110315
68.93	17.28	5.9	8.9	110270
76.81	16.99	5.9	7.4	150227
76.81	15.91	6.4	7.0	150220
84.57	13.63	6.1	8.3	130220
84.56	13.06	5.8	6.3	130227
92.22	12.01	6.9	10.1	110227
92.23	10.98	7.8	9.1	110220
99.74	11.66	7.1	8.7	150280
107.14	10.61	8.0	8.7	130280
114.41	11.81	9.1	9.9	110280
125.80	16.38	5.7	6.4	150235
125.82	16.00	8.5	7.8	150250
132.78	21.56	6.0	8.4	130235
132.78	20.76	7.5	7.4	130250
139.66	22.30	7.2	7.8	110250
139.66	23.78	6.5	7.9	110235

AVERAGE X-SEC 0 MB/STR 0 NOTE

INTEGRATED X-SEC 245.08 MB ERROR 7.1 PER CENT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21
C
EN= 8.56 MEV
LEVEL (S)
4.430
ORNL
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 22

Partial and Total Cross Sections

In our energy range if we sum the elastic and inelastic cross sections to the 4.43-MeV level, we should obtain the total cross section. Total cross sections obtained thusly are compared in Table 23 with the directly measured total cross sections from BNL-325 (second edition) and the ENDF/B file. The error on the sum of the elastic and inelastic cross sections was taken as ±7% since this is the major contribution to the total error. Because of our finite incident neutron energy spread and the resonant structure of the total cross section, an uncertainity of 25 to 50 mb may result in some cases. The values shown for the ENDF/B file will be discussed later.

For 9 of the 13 energies there is fairly good agreement with the total cross sections. At 4.60 and 6.01 MeV our values are significantly higher and at 7.60 and 8.04 MeV are significantly lower than the total cross section. At 4.60, 6.01, and 8.04 MeV the disagreement is less than two standard deviations, whereas at 7.60 MeV it is closer to three standard deviations. These general observations tend to confirm that our

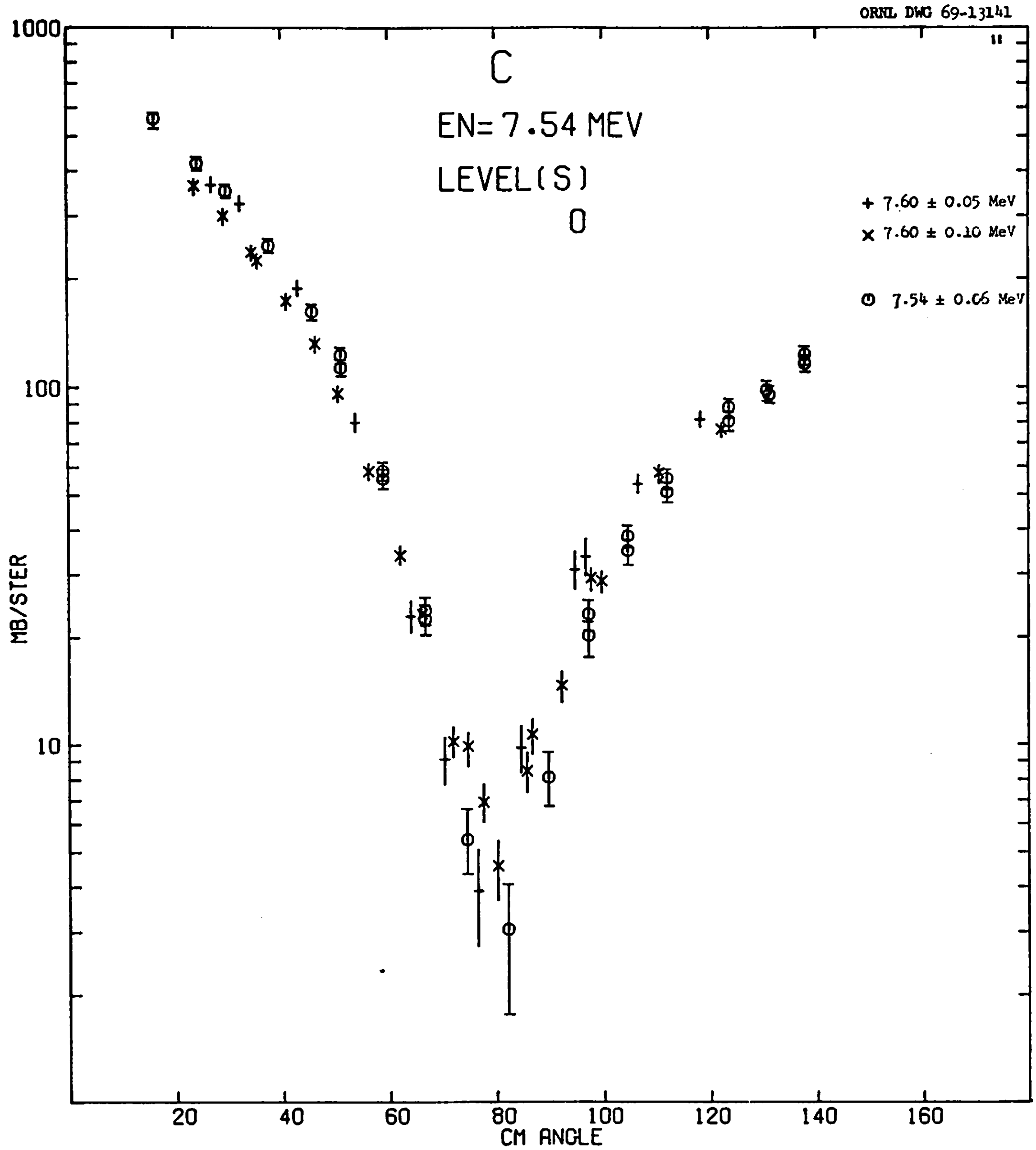
Table 23. Comparison of Total Cross Sections

Neutron Energy (MeV)	Integrated Cross Sections (mb)						
	This Experiment			BNL-325	ENDF/B File		
	Elastic	Inelastic	Total	Total	Elastic	Inelastic	Total
4.60 ± 0.05	1672 ± 124		1672 ± 124	1500	1495		1495
5.04 ± 0.04	1140 ± 83			1200	1146		
5.44 ± 0.17	1107 ± 79			~1150	1030		
5.56 ± 0.05	1060 ± 78			1075	960		
6.01 ± 0.07	965 ± 68	249 ± 102	1204 ± 123	1100	864	222	1086
	863	223	1086				
6.37 ± 0.13	1158 ± 83	236 ± 20	1394 ± 98	~1400	922	372	1294
6.44 ± 0.07	860 ± 61	262 ± 20	1122 ± 79	1100	777	335	1112
7.03 ± 0.06	601 ± 43	167 ± 12	768 ± 54	750	551	190	741
7.54 ± 0.06	1305 ± 93	302 ± 22	1607 ± 112	1700	1305	351	1656
7.60 ± 0.10	1076 ± 77	273 ± 23	1349 ± 94	1650	1396	347	1743
	1317	333	1650				
8.04 ± 0.05	1203 ± 91	409 ± 29	1612 ± 113	1850	1263	490	1753
	1381	469	1850				
8.50 ± 0.08	839 ± 60	248 ± 17	1087 ± 76	1050	737	294	1031
8.56 ± 0.05	803 ± 57	245 ± 17	1048 ± 73	1050	718	290	1008

estimate of ±7% for the standard deviation is realistic. However, it is not clear what role our limited angular range plays in this picture. In Table 23 we have also shown for 6.01, 7.60, and 8.04 MeV the effect of renormalizing our data on the basis of the total cross section disagreement, although we are not sure that the root of the disagreement is an overall error in the normalization for all cases. In the case of the 7.60-MeV data, where the disagreement is the highest, the situation is not very clear. On Figs. 23 and 24 three sets of data are shown around 7.5 MeV: data at 7.54 ± 0.05 and 7.60 ± 0.10 MeV of this report and a measurement at 7.60 ± 0.05 MeV previously reported.[3] The experimental data for this last measurement were not reduced in the same manner as the others;in particular, the error analysis was far less complete. (The numerical values of these data are given in the Appendix.) Because of the different energy spread used in each experiment, the slightly different incident energy, and the presence of a sharp rise in the total cross section about 7.7 MeV, it is not evident that the three sets of data really should be more similar than they are. The only suspicious thing in these data is the lower value of the elastic scattering at 7.60 ± 0.10 MeV for angles less than 60°, and most of the low values that we obtained in the integrated elastic cross section may be due to this. The inelastic-scattering data show a smooth trend for the three sets of data at all angles. The same sets of data are given in Figs. 25 and 26 except that the 7.60 ± 0.10 MeV data have been increased by 18% to remove the total cross section discrepancy. Although now the elastic scattering for the two sets of data at 7.60 MeV are in better overall agreement, there is a systematic disagreement in the inelastic data. To conclude, we have not been able to understand the exact nature of the disagreement in the total cross section for the 7.60 ± 0.10 MeV data.

Comparison with Other Data

Previous measurements of elastic and inelastic cross sections of neutrons from carbon have been made in the energy range of this experiment. Most of them can be directly compared with our data because the energies correspond closely to those of our measurements. The earliest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C
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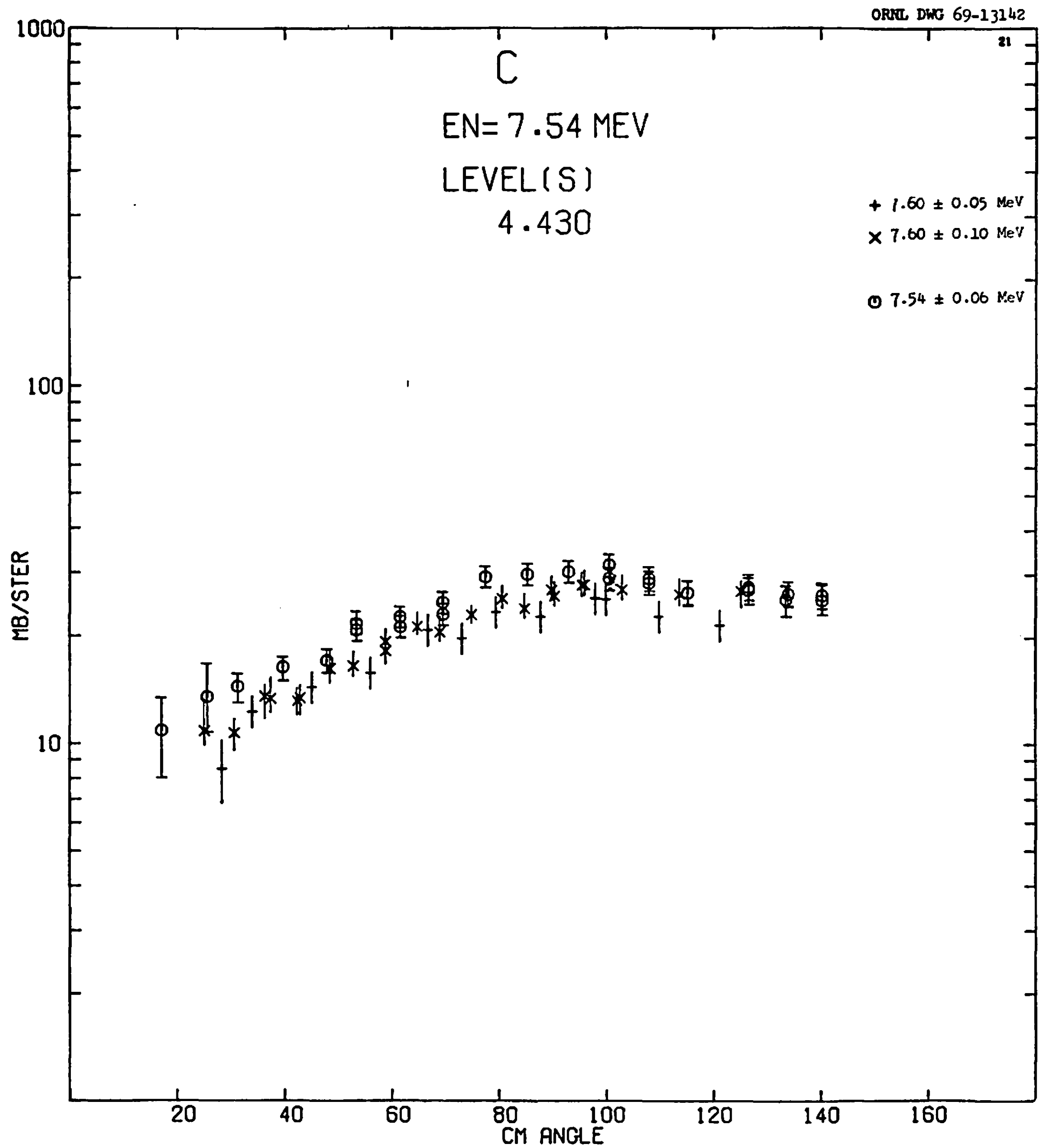
LEVEL(S)
0
+ 7.60 ± 0.05 MeV
× 7.60 ± 0.10 MeV
ʘ 7.54 ± 0.06 MeV
MB/STER
1000
100
10
20
40
60
80
100
120
140
160
CM ANGLE

Figure 23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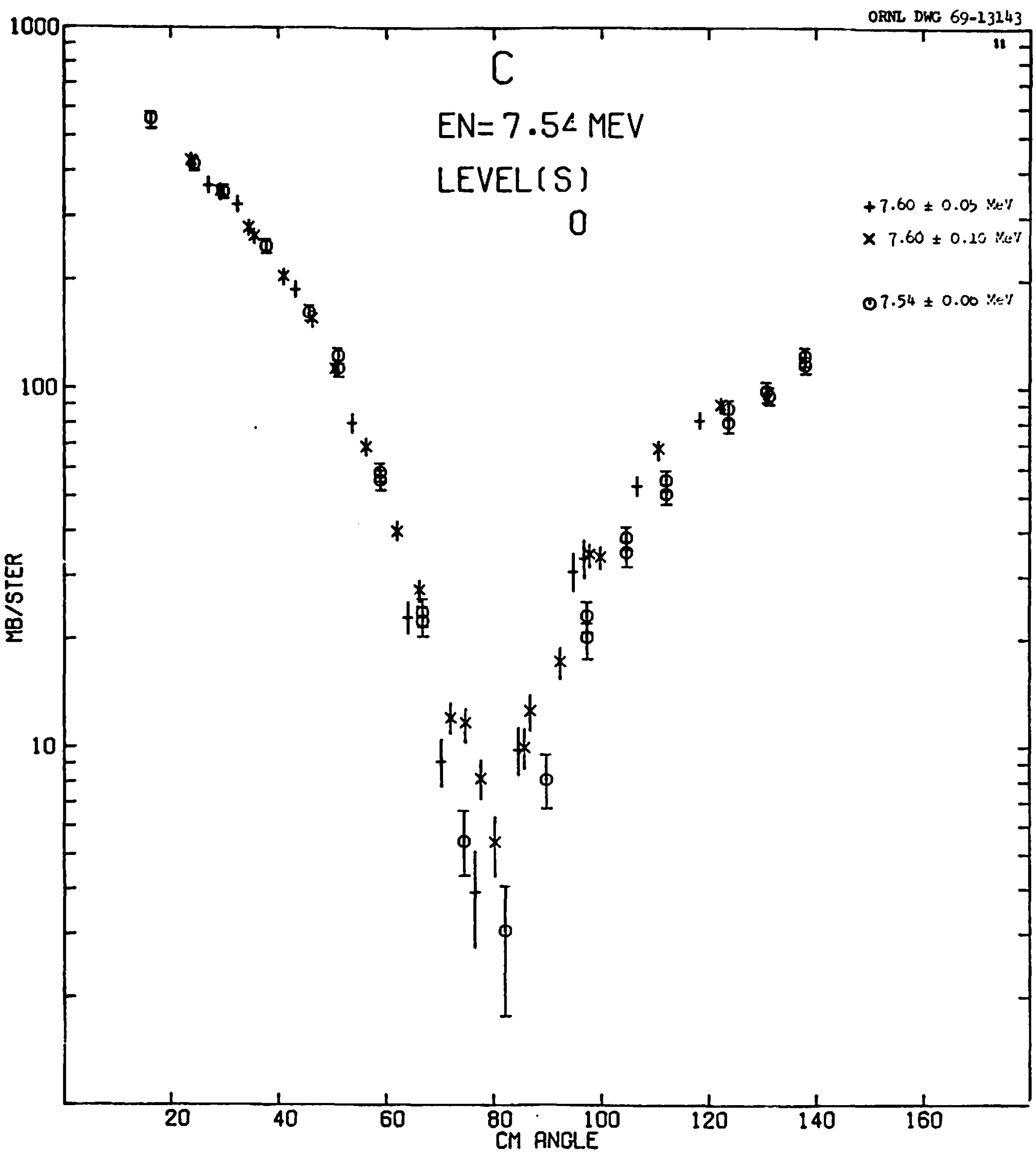
× 7.60 ± 0.10 MeV
Φ 7.54 ± 0.06 MeV
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 24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× 7.60 ± 0.10 MeV
⊙ 7.54 ± 0.06 MeV
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 25

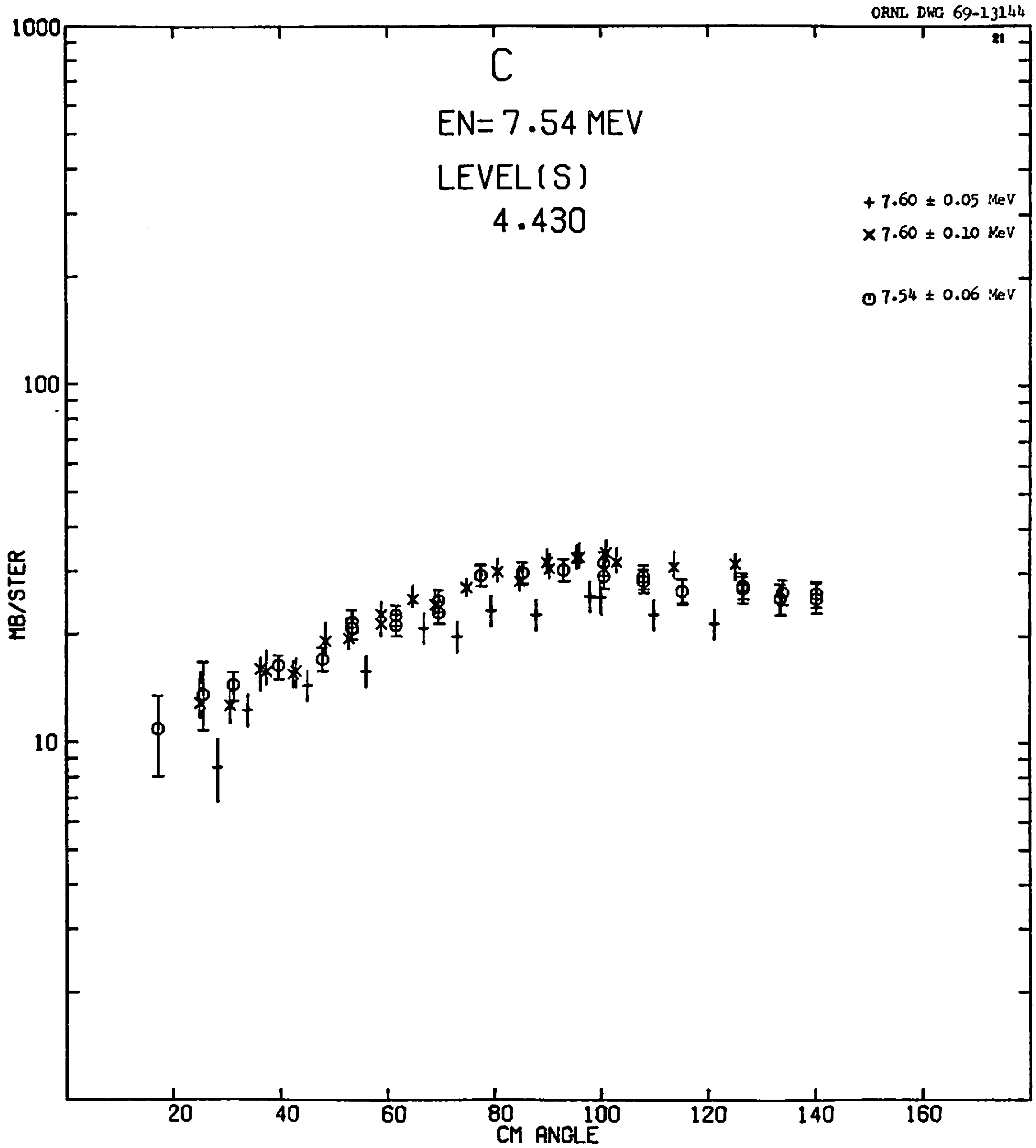

ORNL DWG 69-13144
21
C
EN= 7.54 MEV
LEVEL(S)
4.430
+ 7.60 ± 0.05 MeV
× 7.60 ± 0.10 MeV
⊕ 7.54 ± 0.06 MeV
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 26

measurements at 5.0,[4] 5.6,[5] and 7.0[6] MeV were made using a biased scintillator technique. The later measurements at 6.0,[7] 6.0 and 7.0,[8] and 7.58[9] MeV were made using time-of-flight techniques also. The comparisons of our data with the older data are shown in Figs. 27 through 33 and are described below.

1. At 5.04 MeV (Fig. 27) the agreement is fair up to 110°, with serious discrepancies existing only for the larger angles.

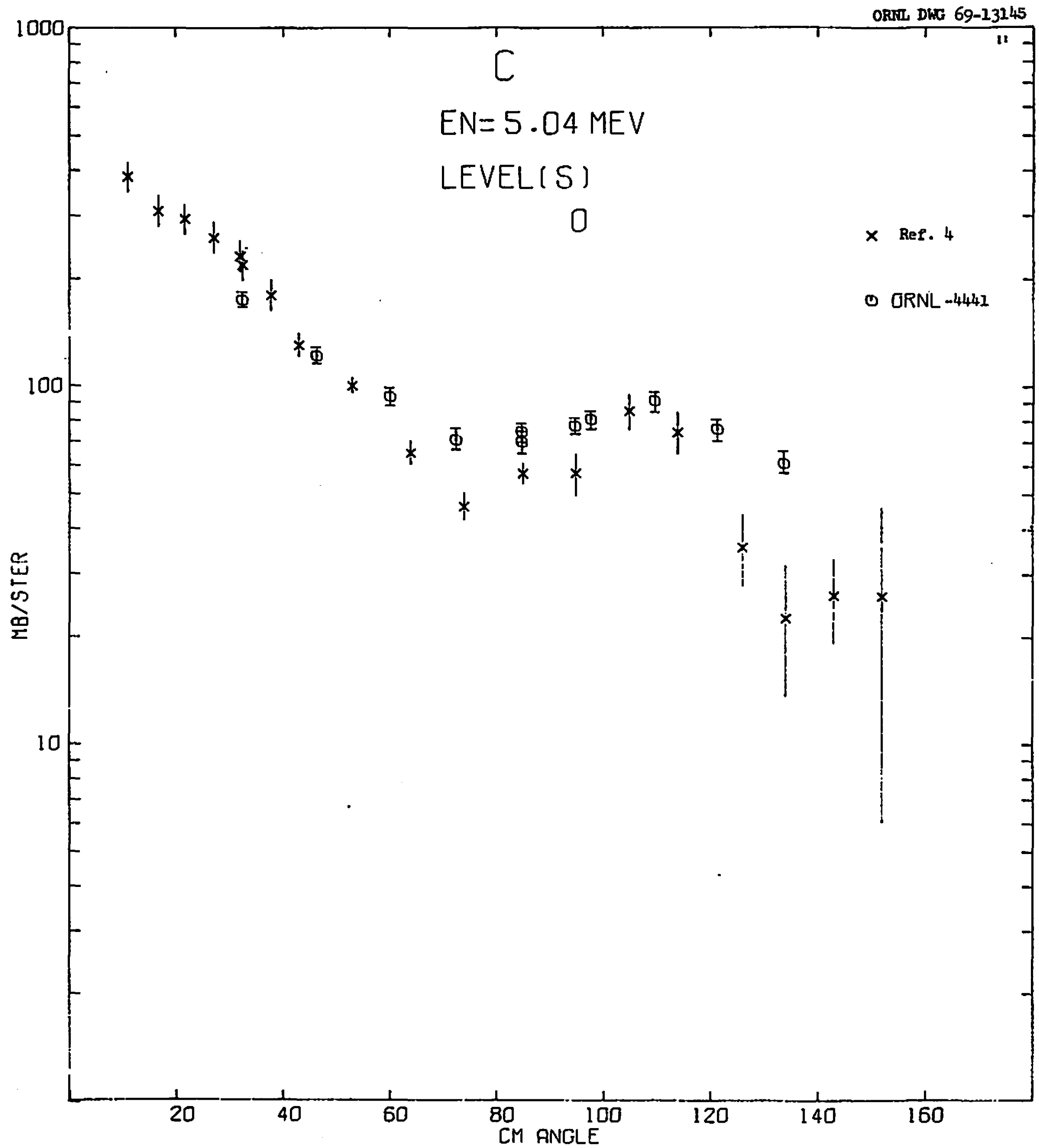
2. At 5.56 MeV (Fig. 28) the agreement is good up to 100°, with serious discrepancies existing for larger angles.

3. At 6.01* MeV (Figs. 29 and 30) the agreement is relatively good over the complete angular range. Our data are systematically higher for both the elastic and inelastic cross sections. A renormalization of our data by about 10%, as suggested by the disagreement in the total cross section, would bring the three sets of data into very good agreement.

4. At 7.03 MeV (Figs. 31 and 32) the three sets of data on elastic scattering are in fairly good agreement. For the inelastic cross section our data for angles greater than 90° are systematically lower.

5. At 7.54 MeV (Fig. 33) the agreement between the two sets of data is very poor. However, this is not surprising since (a) the data of Bostrom et al.[9] were normalized to yield approximately the then poorly known integrated cross section; their estimated error on the normalization is ±25%; (b) although their scatterer was much larger than ours (3.81 cm in diameter, 4.44 cm long), they state that finite size corrections to their data should be small - not more than 10% - and consequently did not apply them. Our own calculations show that because of the large dip at about 80° the corrections are much higher than they

*We have noted a slight discrepancy in the paper of Wilenzick et al.[7] If we perform a Legendre polynomial fit to the data in Table 1 of their paper, we find 1043 and 266 mb as the integrated cross sections for elastic and inelastic scattering instead of the 890 and 225 mb that they claim. Our values of their partial cross sections add up to 1309 mb for the total cross section instead of 1115 mb that they intended. In multiplying the numbers we found by 1115/1309, we obtained their values and therefore conjecture that they intended the values of the cross sections in Table 1 of their paper to be multiplied by 1115/1309. In Figs. 29 and 30 of this report we have applied this renormalization to their data.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LEVEL(S)
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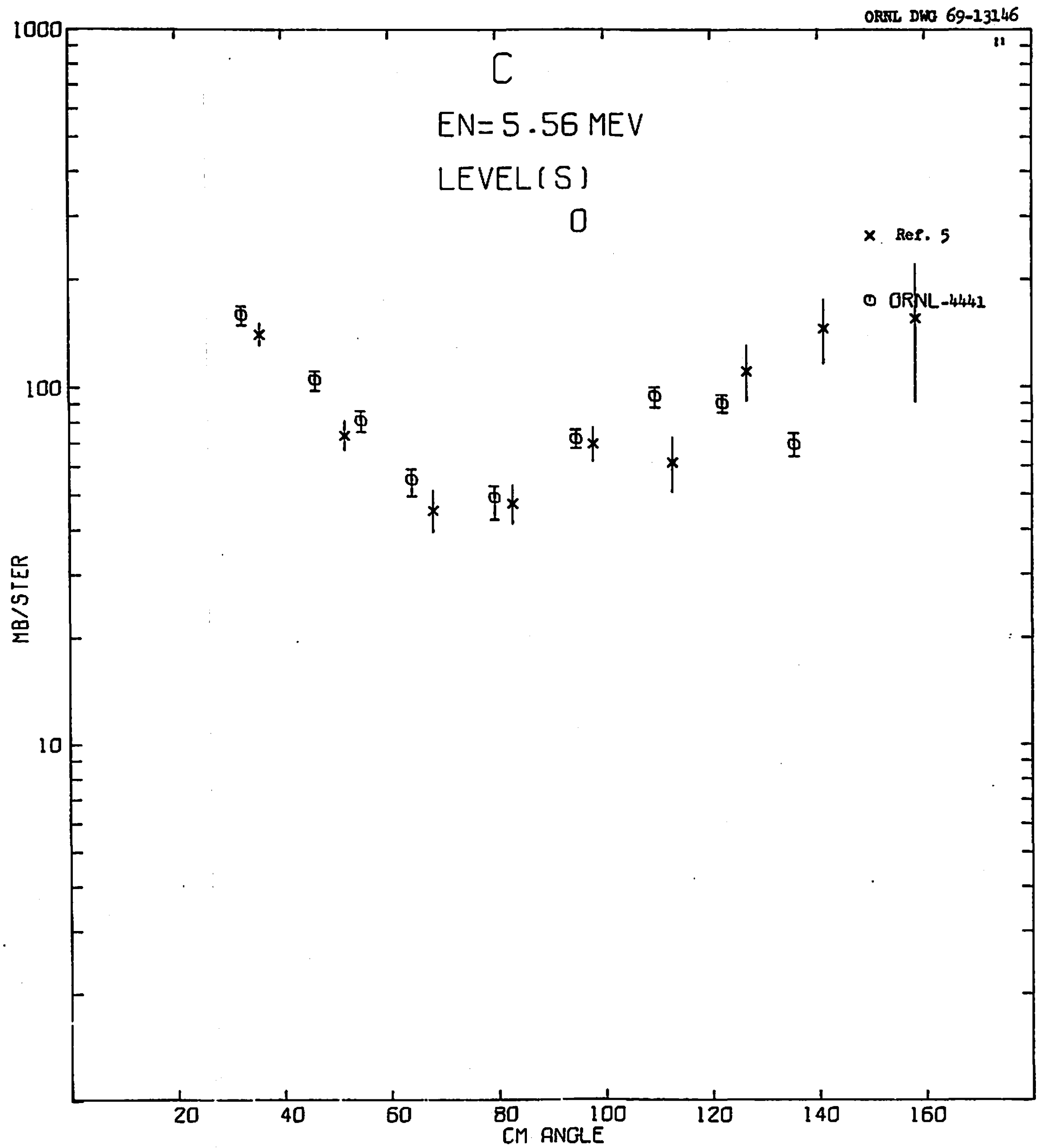
× Ref. 4
ORNL-4441
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 27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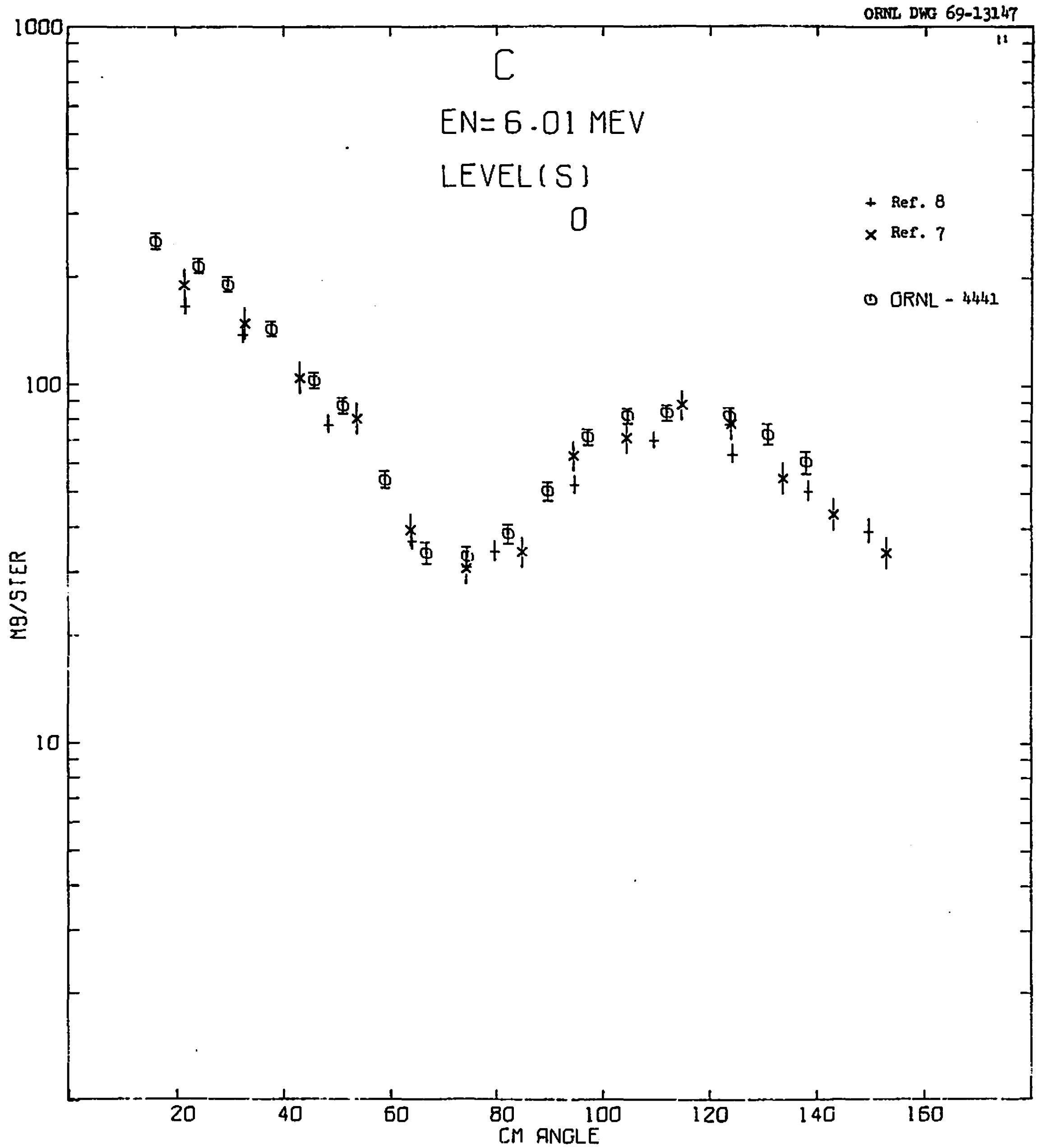
EN= 5.56 MEV
LEVEL(S)
0
× Ref. 5
⊙ ORNL-4441
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 28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EN=6.01 MEV
LEVEL(S)
0
+ Ref. 8
× Ref. 7
ORNL - 4441
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 29

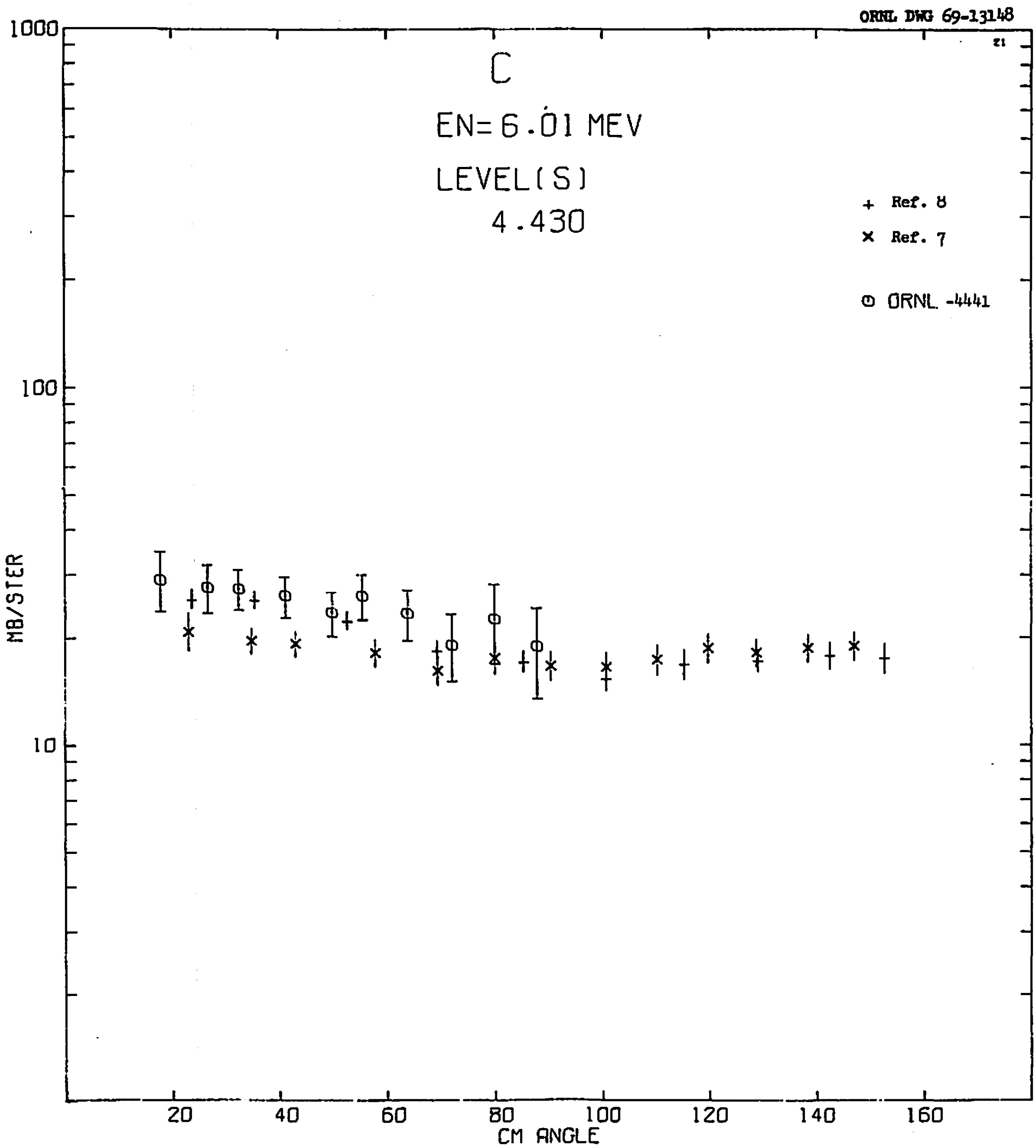
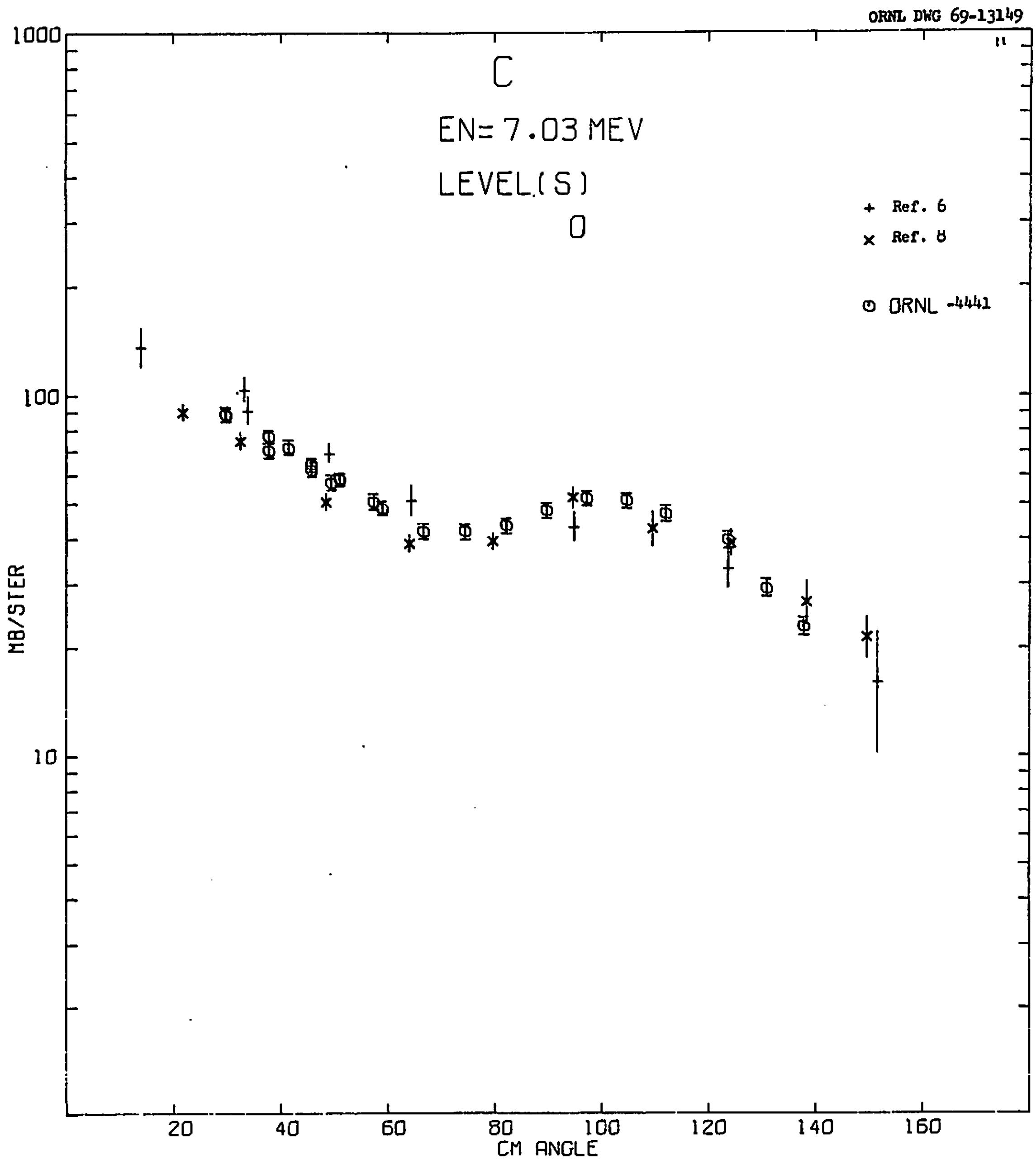

ORNL DWG 69-13148
1000
100
10
C
EN=6.01 MEV
LEVEL(S)
4.430
+ Ref. 8
× Ref. 7
ORNL -4441
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 30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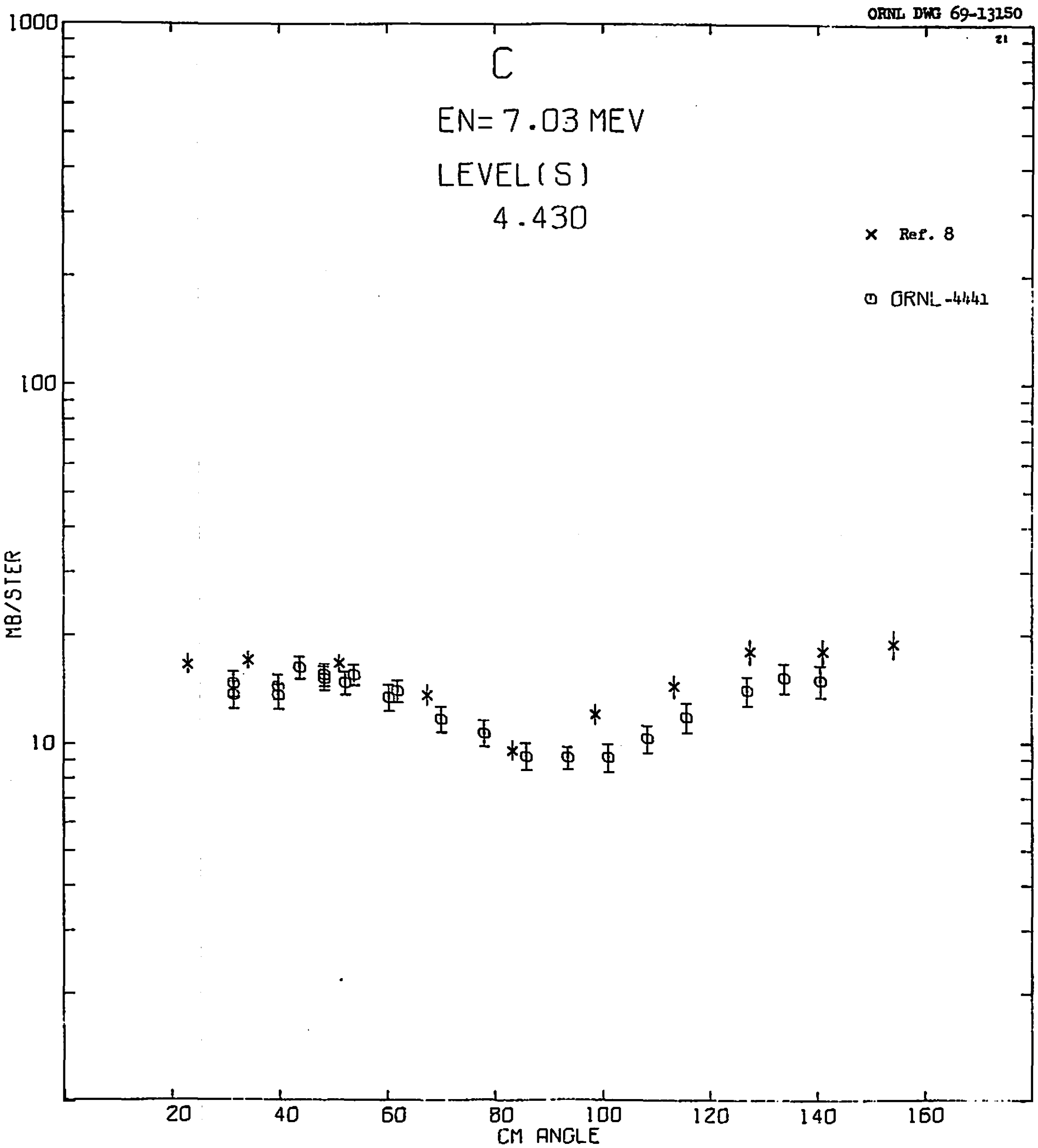
LEVEL(S)
0
+ Ref. 6
× Ref. 8
ORNL -4441
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 31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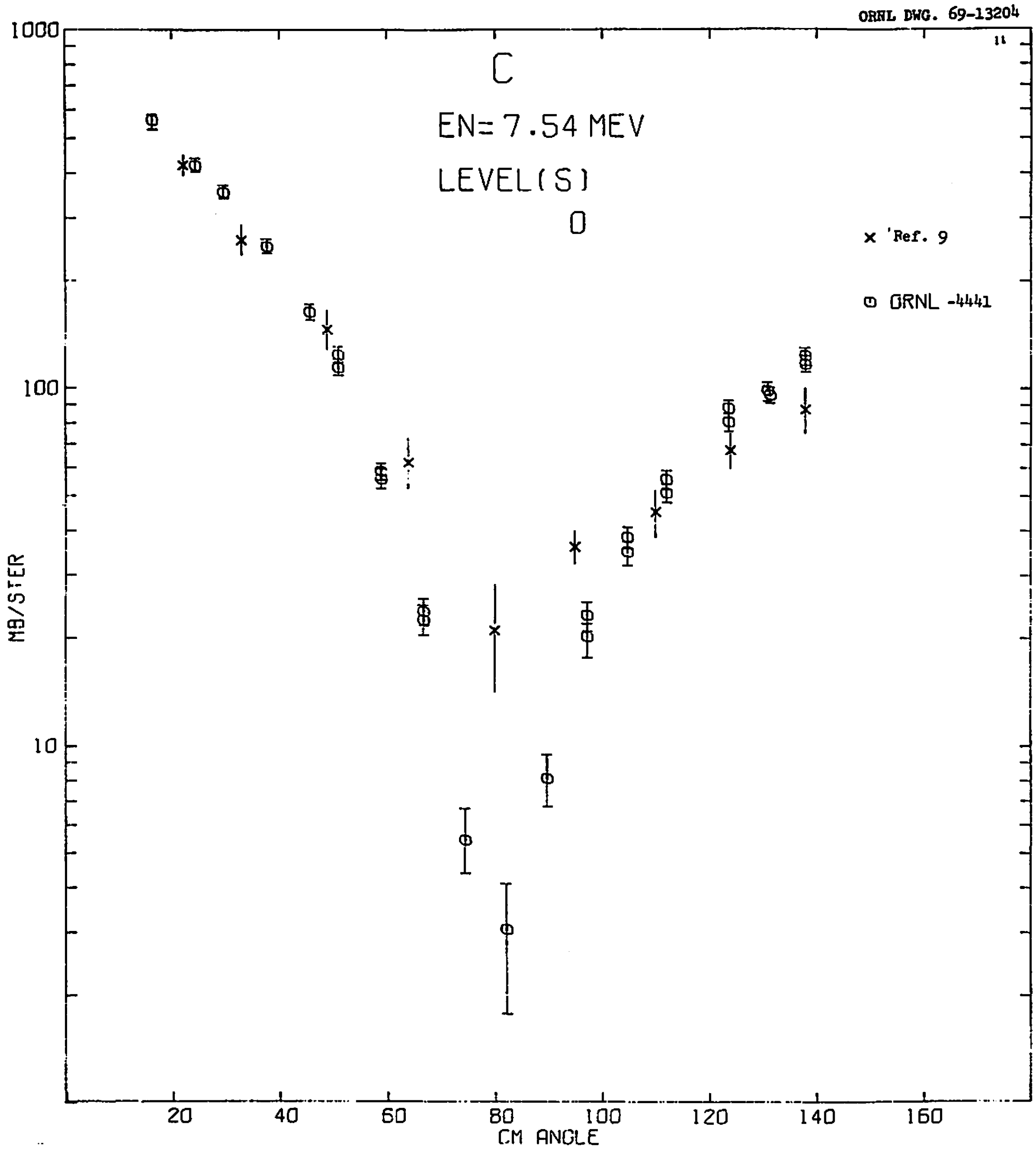
C
EN= 7.03 MEV
LEVEL(S)
4.430
× Ref. 8
ɸ ORNL-4441
MB/STER
1000
100
10
20
40
60
80
100
120
140
160
CM ANGLE

Figure 32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C
EN= 7.54 MEV
LEVEL(S)
0
× Ref. 9
ο ORNL -4441
1000
100
10
MB/STER
20
40
60
80
100
120
140
160
CM ANGLE

Figure 33

claim. For our size of scatterer, in the minimum at about 80°, the corrected microscopic cross section is only about 30% of the observed uncorrected cross section. Our uncorrected cross sections are in fair agreement with their data.

At other energies we have also been able to make a comparison of the shape of our angular distributions with some preliminary data from the University of Kentucky,[10] and found generally good agreement with our data.

Comparison with ENDF/B File

The ENDF/B file of "evaluated" cross sections for carbon was used to generate angular distributions for elastic and inelastic scattering at our incident neutron energies. The magnitude of the cross sections and of the Legendre polynomial expansion coefficients was obtained at the appropriate energies by the recommended interpolation procedure. In order to take into account the finite energy spreads of the experiments, the cross sections were obtained at energies $E_0 - \Delta E$, E_0, and $E_0 + \Delta E$, where E_0 is the incident neutron energy and $\pm\Delta E$ the neutron energy spread. The magnitude of the cross sections and of the Legendre coefficients at the three energies was then combined with the following weights: $\frac{1}{4}$ at $E_0 \pm \Delta E$ and $\frac{1}{2}$ at E_0.

There is in general poor agreement between our data and the ENDF/B file, as can be seen in Figs. 1 through 22 and in Table 23. However, this is not too surprising since the evaluation on carbon was performed with rather scant experimental information on both the shape and the magnitude of the cross sections in the energy range covered by our experiment. The only extensive experimental information available in this energy region on inelastic scattering was an excitation function of 4.43-MeV gamma rays measured at 90° (Ref. 11). Since the gamma-ray angular distribution need not be isotropic, this measurement is not adequate to determine the inelastic cross section. Some of the lack of agreement in the magnitude of the cross section for both elastic and inelastic scattering must be attributed to this. Some of the disagreement in the shape of the angular distributions can be attributed to inadequate data. For instance, the ENDF/B file at 7.54 MeV reproduces quite well the uncorrected data of Bostrom *et al.*[9]

CONCLUSIONS

The data presented in this report increase considerably our knowledge of the carbon cross sections. The data are in good agreement with previously available data in the energy range 4.5 to 8.5 MeV. The present ENDF/B file of "evaluated" cross sections on carbon is felt to be rather inadequate in the same energy range. However, in view of the resonance structure of the data we feel that more measurements are required on carbon in this energy range before an adequate set of "evaluated" cross sections can be reliably established for this important nucleus.

ACKNOWLEDGMENTS

Numerous persons have contributed to this experimental program at one time or another and we would like to thank them for their contributions. In particular we would like to acknowledge the help of J. K. Dickens, J. W. McConnell, J. A. Biggerstaff, A. M. Marusak, P. H. Stelson, C. O. LeRigoleur, and M. V. Harlow. We would also like to thank J. L. Weil of the University of Kentucky for permitting us to see their preliminary results and R. Q. Wright of the Computing Technology Center, Union Carbide Corporation, Oak Ridge, for his help in obtaining the ENDF/B cross sections.

APPENDIX

The following cross sections were reported[3] previously. A rather inadequate error analysis on these data caused us to report errors of ±5% on the final data. This error, we now realize, is more typical of the uncorrected data and should not apply to the final data. In the light of our more extensive recent analysis of data and our successful method of propagating errors throughout the data reduction process, we find it necessary to revise the previous errors on those data. The errors shown below are not the result of reprocessing our data with a better error propagation scheme, but are based solely on typical errors which we subsequently found realistic for the data given in the body of this report. The incident neutron energy was 7.60 MeV and the energy spread in the beam was ±0.05 MeV. The scattering sample was the same as that described in this report.

Elastic			Inelastic (Q = -4.43 MeV)		
θ_{cm} (deg)	σ_{cm} (mb/ster)	Error (%)	θ_{cm} (deg)	σ_{cm} (mb/ster)	Error (%)
27.0	366	5	28.3	8.5	20
32.4	324	5	33.9	12.3	10
43.1	188	5	45.1	14.4	10
53.7	80	6	56.0	15.8	10
64.1	22.9	10	66.8	20.9	10
70.3	9.1	15	73.1	19.8	10
76.5	3.9	30	79.4	23.4	10
84.7	9.8	15	87.8	22.8	10
94.8	30.8	12	97.9	25.7	10
96.8	33.5	12	99.9	25.5	10
106.7	53.6	6	109.8	22.8	10
118.3	81.4	5	121.1	21.5	10

REFERENCES

[1] R. E. Textor and V. V. Verbinski, 05S: A Monte Carlo Code for Calculating Pulse Height Distributions Due to Monoenergetic Neutrons Incident on Organic Scintillators, ORNL-4160 (February 1968).

[2] S. A. Cox, Nucl. Inst. Methods 56, 245 (1967).

[3] F. G. Perey et al., Bull. Am. Phys. Soc. 12, 512 (1967).

[4] R. W. Hill, Phys. Rev. 109, 2105 (1958).

[5] J. E. Braley and C. N. Cook, Phys. Rev. 118, 808 (1960).

[6] J. R. Beyster, M. Walt, and E. W. Salmi, Phys. Rev. 104, 1319 (1956).

[7] R. M. Wilenzick et al., Nucl. Phys. 62, 511 (1965).

[8] E. Haddad and D. D. Phillips, Bull. Am. Phys. Soc. 4, 358 (1959).

[9] N. A. Bostrom et al., Neutron Interactions in Lithium, Carbon, Nitrogen, Aluminum, Argon, Manganese, Yttrium, Zirconium, Radiolead, and Bismuth, WADC-TN-59-107 (1959).

[10] J. L. Weil, University of Kentucky, private communication, October 1969.

[11] H. E. Hall and T. W. Bonner, Nucl. Phys. 14, 295 (1959).

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