MASTER

THE MEASUREMENT AND ANALYSIS
OF NEUTRON CROSS SECTIONS WITH
THE OAK RIDGE LINEAR ACCELERATOR
NEUTRON FACILITY

Progress Report
for Period April 1, 1978 - March 31, 1979

J.B. Garg
Physics Department
State University of New York at Albany
Albany, New York 12222

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

December 1978

Prepared For
The U.S. Department of Energy,
UNDER CONTRACT NO. Ey-76-S-02-2439

DISCLAIMER

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

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe privately owned rights.

Abstract

The research work conducted under the USD0E contract EY-76-S-02-2439.A002 involved the measurement, analysis and interpretation of high resolution neutron total and capture cross sections in the neutron energy range of few eV to few hundred keV with many nuclei. Some of these measurements on (V, Mn, Co) performed with the Columbia University's neutron velocity selector many years ago have been analyzed and published in the Nucl. Science and Engineering (1978). The measurements on separated isotopes of iron and zinc which were performed with the Oak Ridge electron linear accelerator neutron facility have been analyzed using the area and the R-matrix shape analysis, to determine values of resonance parameters such as resonance energies (E_0), neutron widths (Γ_n), capture widths (Γ_γ), J^π -assignment of resonances and the average values of these parameters. An interpretation of these results in term of statistical theories and optical model interaction has been made. These results will shortly be submitted for publication. The high resolution total cross sections in the two isotopes of chromium (A=50, 52) and yttrium, which have been measured up to 500 keV, are in the process of being analyzed.

I. INTRODUCTION

This technical progress report describes the collaborative research work carried out with the various scientific groups during the contract year (1978-79) on the high resolution measurements of neutron total and capture cross sections in certain nuclei of interest to the development of atomic energy.

The measurements of neutron total and capture cross section in nuclei provide valuable data for nucleosynthesis of elements, and a better understanding of the neutron interaction with nuclei. The later information is obtained via investigation of the level resonance parameters and their statistical averages such as the level spacing for given angular momentum and spin, Γ_n and Γ_γ and strength function. The systematics of resonance levels such as spin and parity and their dependence on strength function, level density etc., are also important. The capture cross section measurements are complimentary to the measurements of neutron total cross sections.

These measurements in certain nuclei are equally important for their application in the reactor design. The measurements in the separated isotopes of iron, zinc and chromium were undertaken to obtain more precise values of the above mentioned quantities, than is available at present.

The high resolution total cross section measurements in yttrium nucleus were undertaken in order to locate the intermediate states as has been predicted by the theorists. In addition the measurements of neutron capture γ -ray spectroscopy in erbium isotopes performed with the Brookhaven fast chopper facility is described.

During this period some effort was also spent in modifying various computer programs of data transfer, area and shape analysis of neutron total cross sections data, LSFIT code for capture area analysis and the MULTI program for the R-matrix analysis of total cross section data. We are now using these programs at Albany with our UNIVAC 1110 computer.

The detailed accomplishment of the research work is given in the following pages:

I. Neutron Resonance Spectroscopy in V, Mn and Co
J.B. Garg, State University of New York at Albany.

High resolution total neutron cross section measurements in natural vanadium, manganese and cobalt which were made in the energy range up to a few hundred keV with the Columbia University's Nevis neutron velocity spectrometer have been analyzed with a R-matrix multi-level code and the resonance parameters (E_λ , Γ_n , J^π , S_0 , $\langle D \rangle$) have been obtained. In addition making use of the published thermal energy data, the parameters of the bound levels were also determined.

A paper describing the details of these results has been published in the Journal of Nuclear Science and Engineering 65, 76-92 (1978).

II. Research Work Performed At The Oak Ridge National Laboratory Using ORELA Neutron Facilities. J.B. Garg and V. Tikku (SUNYA), J.A. Harvey, R.L. Macklin and J. Halperin (ORNL).

II(a) Neutron Total Cross Section And Resonance Parameters Of ^{58}Fe
J.B. Garg (SUNYA) and J.A. Harvey (ORNL).

Neutron total cross section measurements in the energy range from 30 eV to 500 keV have been made using a pulsed neutron time-of-flight method with a 78.2 m flight path and a nominal resolution of about 0.007 ns/m. From the analysis of the data up to 350 keV we have obtained values of the s- and p-wave neutron strength functions and of the mean level spacings. These are $S_0 = (3.2 \pm 1.4)$, $S_1 = (0.68 \pm 0.13)$ in units of $10^{-4} \text{ eV}^{-1/2}$, $\langle D \rangle_{\ell=0} = (32 \pm 12) \text{ keV}$ and $\langle D \rangle_{\ell=1} = (8 \pm 1) \text{ keV}$. This paper has been published in the Physical Review C18, 1141 (1978).

II(b) Neutron Total Cross Section In ^{57}Fe
J.B. Garg (SUNYA) and J.A. Harvey (ORNL).

The total neutron cross section in the separated isotope

of ^{57}Fe (enriched to 99%), has been measured up to 500 keV using ORELA facilities. These data have been analyzed and a paper describing the results is in preparation.

II(c) Neutron Total Cross Section In Isotopes Of Chromium
J.B. Garg, V. Tikku (SUNYA) and J.A. Harvey (ORNL).

The total neutron cross section in the separated isotopes of chromium ($A=50, 52$) have been performed with ORELA neutron time-of-flight facility at 78.2 meter station. The raw data has been stored in the magnetic tapes and will be processed for the determination of σ_T vs E_n values after making corrections for counting rate dead time and background subtraction. The partial analysis of these data will also be completed during the contract period.

II(d) Total Cross Section in the Separated Isotopes of Zinc
J.B. Garg, V. Tikku(SUNYA) and J.A. Harvey, N.W. Hill (ORNL).

Total neutron cross sections in the isotopes of $^{64}_{30}\text{Zn}$ ($A=64, 66, 67, 68$ and 70) had been performed using ORELA facilities. These isotopes were obtained from Oak Ridge Isotope Division and from the Los Alamos Scientific Lab. The isotopes were in the form of powdered oxides with the respective enrichment as given in Table I. The samples were packed in a container of polyethylene tubing of dimensions (ID = 2.64 cms and different heights depending upon the amount of material available). Two sets of measurements were made, one emphasizing the high energy region using the NE 110 fast scintillators and one emphasizing the low energy region using a Li-glass scintillation detector. Both these sets of measurements were made at a flight path of 78.2 meters and an electron burst width of 5 ns. The channels of the time-of-flight analyzer were varied

from a minimum of 1 ns up to the maximum value of 512 ns depending upon the energy region to be measured. Samples of U^{238} and $3''CH_2$ were also used simultaneously for the determination of the background.

The energies of resonances and the tentative l -assignment made from the shape of the resonances in the various isotopes were given in the previous C00-2439-3. These data have now been analyzed for the determination of the resonance parameters (E_0 , J^π , Γ_n) with the R-matrix and MULTI Codes. The analysis for ^{64}Zn , ^{66}Zn , ^{68}Zn and ^{70}Zn isotope has been completed to date. The analysis of the isotope ^{67}Zn is in progress and will be completed by the end of the contract year. The resonance parameters of these nuclei are given in Tables (II, III and IV). The results of these investigations are being prepared for publication in the Physical Review.

III. High Resolution Neutron Capture Cross Section Measurements

III(a) Neutron Capture Cross Section of Manganese

J.B. Garg (SUNYA) and R.L. Macklin and J. Halperin (ORNL)

Neutron capture cross section measurements of ^{55}Mn have been carried out at the ORELA time-of-flight facility over the energy interval of 2.6 to 600 keV. These measurements were carried out with the total energy detector at the 40 m flight path which has been previously described. The total capture width, Γ_γ , has been evaluated for 143 resonances (up to 110 keV) from the measured capture areas and from published neutron widths¹. The resonance parameter analysis was carried out in terms of the single level Breit Wigner formula using the method of least squares. Account was taken of instrumental resolution, Doppler broadening and resonance self-protection. The asymmetric shape of the detector response was fitted to a Gaussian function with an exponential tail. For broad resonances, it was

Table I

Atomic Percentage of Masses in the Separated
Isotopes of Zn used for the Measurement

Mass	Isotopes				
	^{64}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{70}Zn
64	97.87	0.35	1.66	0.26	5.08
66	1.18	99.35	4.46	0.27	3.71
67	0.21	0.12	89.68	0.19	0.81
68	0.74	0.19	4.15	99.28	4.46
70	<0.05	<0.05	<0.05	<0.1	85.9

Table II-S-Wave Resonance Parameters of ^{64}Zn

E_0 (eV)	Γ_n (eV)
2627	67.5
4170	19.3
10775	95
13019	189
15212	109
21316	66.8
22676	77.6
29100	56.2
29640	78.9
30708	200
32450	490
47955	218
50700	126
52120	127
54300	64
60882	9.9
67440	168
68932	42.6
78345	35
78753	53.5
83570	202
87350	177
89520	395.7
94832	138.6
96555	31.8
108080	128
111680	27.4
114075	108
120432	76.6
121757	171
132600	418
134352	234
140797	55.5
142806	311
148120	327
150380	209
155024	142
157400	657
159315	219
168386	38.9
170565	351
178500	1056
180800	119
185054	425
186780	30
188500	19
193740	141
196175	29
202560	47
205115	656
213640	138

<u>E_o (eV)</u>	<u>Γ_n (eV)</u>
215875	408
219200	201
225730	27
230250	64
236530	1021
239110	224
243780	148
248910	1122
254767	1135
258870	142
262530	1486
265010	1467
268600	165
272280	130
273817	81
276150	236
284970	69
292545	2704
305999	1825
312290	1956
314460	2918
317115	231
318970	225
320400	141
323520	199
332700	519
337360	1161
339130	175.1
342440	304
351100	592
354930	476
360340	2761
367550	1212

E_o (eV)	Γ_n (eV)
4046	5.2
10420	112
14200	570
17055	5.2
19520	289
24310	436
34380	6.8
42640	175
44991	16.9
56780	92.9
64841	145
67999	180
76675	260
79270	3.1
91449	7.5
94425	552
96922	11.8
99086	157
100000	487
108300	88.9
117000	854
120130	745
128510	150
133575	347
136901	1258
139717	38.8
144945	1218
152040	2807
159067	65
165475	55
168415	195
173085	36
177100	168
179890	53
186985	1111
198490	253
203460	293
205770	22.0
210180	73
214175	440
215995	195
219365	403
226940	143
233060	480
236770	131
240150	132
248200	97
250970	425
254320	1109
263965	64
270080	62
271800	26

<u>E_o (eV)</u>	<u>Γ_n (eV)</u>
273830	313
277230	63
282240	1753
284310	479
290270	1077
297630	150
301870	412
306630	221
312620	98
313910	52
316520	309
324299	273
326700	85
334240	431
340320	210
349130	452
352615	415
362145	1354

Table IV - Resonance Parameters of ^{68}Zn

s-Wave Resonances		p-Wave Resonances	
E_0 (eV)	Γ_n (eV)	E_0 (eV)	Γ_n (eV)
514.9	10	16015	7
5044	0.2	18400	5.5
13375	20	20230	1
18815	308	24741	2
20966	3.5	26254	3.4
26504	30	28543	4
34710	40	33507	3.2
39284	7.5	39270	8.5
48000	106	42550	1.5
50544	135	53034	1.5
56729	30	53893	5.2
57560	175	56695	30
65837	1480	62330	10
70900	17	69267	7
71543	108	70900	17
75568	204	76380	9
87000	11	77318	4
93875	600	80759	13.62
96624	920	85670	2.4
99450	561	86690	1.5
105670	140	86970	3.8
110270	1730	87152	22.4
122570	57	88520	7.2
125000	2295	118540	75.4
133000	544	122570	57
139600	70	130090	13.7
142700	1096	136100	6.2
154780	231	140230	12.5
162540	308	140928	4.5
173820	69	146220	2.2
180520	217	149340	4.5
187380	69	150460	4.5
189840	22	151710	2.3
195700	1597	153080	3.5
197200	178	154100	7.5
203320	1172	155320	13.4
215024	765	158740	0.9
218190	1651	159370	21.5
220480	1075	159770	4.0
226380	95	163900	6.1
232130	95	166270	0.5
241400	1660	167480	2.3
247200	1700	168940	0.8
251270	95	172180	1
253234	704	173200	1
254869	772	177250	46.5
264520	1080	182120	5.3
267083	100	184030	1.2
267860	465	185970	19.6
275490	503	186392	6.5
279940	2804	191960	22

$\ell=0$

E_o (eV)	Γ_n (eV)
283490	1916
294560	108
310190	704
315740	379
320920	526
326300	957
333830	306
363630	106
366460	121
375230	354

 $\ell=1$

E_o (eV)	Γ_n (eV)
205227	13.4
208388	31.4
209995	20.7
213558	175
214000	36.7
219936	51
227248	27
230678	22
233487	18
234878	50
236073	35
239240	113
240675	44
244440	41
246090	37
252030	43
257208	18
262897	74
270050	46
272900	49
275072	89
276405	76
281618	39
286865	141
292480	41
298121	30
299350	104
324491	175
329281	139
330526	180
335107	118
342076	241
343426	63
347280	201
348300	89
353221	262
353841	57
371115	90

necessary to include multiple scattering as well as the prompt neutron sensitivity.

The s-wave resonances have been largely identified from the transmission experiments by their characteristic asymmetric shape. The remaining resonances have been assumed to be p-wave except for a small number assigned as d-wave because of their exceptionally small p-wave reduced widths (less than 10^{-2} eV).

The average level spacing has been measured for s-wave resonances as $\bar{D}_{\ell=0} = 2.33(25)$ keV and for p-wave resonances as $\bar{D}_{\ell=1} = 1.32 \pm 0.11$ keV. Their ratio is in good agreement with the $(2J+1)$ expectation

The neutron strength functions defined as

$$S_{\ell} = \left(\frac{1}{2\ell + 1} \right) \frac{\Sigma g \Gamma_n^{\ell}}{\Delta E}$$

have been evaluated here for p-wave resonances and a lower limit established for d-wave resonances. Γ_n^{ℓ} = reduced neutron width for ℓ -wave resonances, g = statistical weight factor and ΔE = energy range spanned. For a value of the nuclear radius, $R = 4.5$ fm, we find $S_1 = 0.35(4) \times 10^{-4} \text{ eV}^{-1/2}$, which is consistent with values obtained for other neighboring nuclei. We also report $S_2 > 1.0 \times 10^{-4} \text{ eV}^{-1/2}$ based on the small sampling of d-wave resonances assigned in this study.

The average radiative widths for 46 s-wave and 28 p-wave levels have been measured as $(\bar{\Gamma}_{\gamma})_{\ell=0} = 0.75(15)$ eV and $(\bar{\Gamma}_{\gamma})_{\ell=1} = 0.40(10)$ eV. The difference would appear to be significant, although the p-wave average is for only 1/3 of the resonances in the energy range due to experimental difficulties.

The correlation between the reduced neutron widths and the total radiative widths have been investigated for s-wave resonances. A correlation coefficient $\rho = 0.64(14)$ has been measured. An

examination of the probability that so high a correlation coefficient could result from a random distribution of these parameters is 0.001 indicating a highly significant correlation, thus implying a non-statistical interpretation, such as doorway states or valency capture.

This paper will be published in the Physical Review, November issue (1978).

1) J.B. Garg, Nucl. Science and Eng. 65, 76 (1978).

III(b) Neutron Capture Cross Section Of Zn Isotopes

J.B. Garg, V. Tikku (SUNYA) and J. Halperin and R.L. Macklin (ORNL)

Neutron capture cross section measurements in separated isotopes of Zn ($A=64, 66, 67$ and 68) have been carried out at the ORELA time-of-flight facility over the energy interval of 2.6 to 600 keV at 40m flight path station. Using the LFSIT Code, these data have been analyzed to determine the capture area under the resonance peaks. Using the values of Γ_n determined from the complimentary measurements of neutron total cross section in these nuclei, we have been able to determine the values of Γ_γ for most of the resonances. For very narrow resonances, whose Γ_n values could not be obtained from the transmission measurements, the assumed average value of Γ_γ was used to determine its neutron widths.

The results of these measurements are given in tables (V and VI) for ^{66}Zn and ^{68}Zn respectively.

III(c) Resonance Neutron Capture γ -rays From Even-Even Erbium

Isotopes, J.B. Garg (SUNYA), R.E. Chrien, H.I. Liou, M. Stelts (Brookhaven National Lab.) and R.C. Greenwood (INEL)

A systematic investigation of the nuclear structure in all the erbium isotopes have been made via (n,γ) capture studies

E_o (keV)	$\frac{g\Gamma(\Gamma_n + k\Gamma_n)}{\Gamma}(\text{meV})$	$g\Gamma_n$ (eV)	Γ_Y (meV)	$k(10^{-3})$	$(\Gamma_Y)_{\text{eff}}$ (meV)	g
3.558	5.79±.18	.0060±.0002	170	0.793	170	1
4.046	194.57±1.83	5.2	202±2	0.750	198±2	1
4.389	49.27±0.64	0.07	156±6	0.730	156±6	1
5.204	2.04±0.19	.0021±.0002	170	0.690	170	1
5.348	85.10±0.77	0.145	206±5	0.650	206±5	1
6.482	2.82±0.55	.0030±.0005	170	0.600	170	1
6.717	138.05±0.99	0.73±0.02	170	0.580	170	1
8.950	3.06±0.42	.0030±.0004	170	0.510	170	1
9.184	99.49±1.27	0.180	223±6	0.510	223±6	1
9.823	133.52±1.46	0.480	93±7	0.500	93±7	2
10.415	470.73±6.99	112.29	473±7	0.480	419±7	1
10.886	116.38±1.37	0.369±0.014	170	0.480	170	1
13.275	6.49±1.04	0.007±0.001	170	0.430	170	1
13.414	33.57±1.56	0.04±0.002	170	0.425	170	1
14.200	1998.81±29.19	570.78	2006±29	0.410	1772±25	1
15.658	216.15±3.19	1.16	133±4	0.400	131±4	2
15.880	27.77±1.59	0.033±0.003	170	0.400	170	1
17.054	292.59±5.18	5.22	310±6	0.380	380±6	1
17.269	245.03±4.14	3.10	133±3	0.380	132±3	2
17.350	11.42±1.53	0.012±.001	170	0.380	170	1
19.550	553.99±11.91	289.37	555±12	0.370	448±12	1
20.726	50.44±1.89	0.072±.004	170	0.366	170	1
20.825	114.41±2.39	0.35±0.02	170	0.366	170	1
21.680	33.88±3.31	.042±.005	170	0.366	170	1
21.710	276.71±5.49	10.0	191±4	0.366	189±4	2
23.076	28.69±1.92	.035±.003	170	0.375	170	1
24.078	242.76±6.54	4.25	258±7	0.380	256±7	1
24.310	717.75±20.67	436.12	719±21	0.385	551±21	1
24.617	20.02±3.12	.23±.004	170	0.390	170	1
25.995	24.20±2.66	.028±.004	170	0.465	170	1
26.433	52.69±3.36	0.20	72±6	0.525	72±6	1
26.705	186.22±4.80	0.86	119±7	0.540	119±7	2
27.387	98.48±3.33	0.234±0.019	170	0.730	170	1
28.523	3.44±2.24	0.004±0.002	170	0.786	170	1
28.864	20.23±2.92	0.023±0.004	170	0.786	170	1
29.017	39.72±3.36	0.052±0.006	170	0.760	170	1
29.363	201.58±5.46	1.0	253±9	0.740	252±9	1

E_o (keV)	$\frac{g\Gamma_n(\Gamma_\gamma + k\Gamma_n)}{\Gamma}$ (meV)	$g\Gamma_n$ (eV)	Γ_γ (meV)	$k(10^{-3})$	$(\Gamma_\gamma)_{eff}$ (meV)	g
31.038	113.61±4.50	0.36	166±10	0.700	166±10	1
33.735	142.25±5.30	1.11	163±7.0	0.580	162±7	1
34.385	221.94±7.27	6.86	229±8	0.575	225±8	1
34.934	257.23±7.11	2.2	146±6	0.575	145±6	2
35.169	30.69±4.04	0.37±.006	170	0.550	170	1
35.976	150.91±6.23	2.10	163±7	0.550	162±7	1
36.856	142.80±5.89	1.55	157±7	0.520	156±7	1
37.478	228.14±7.32	1.14	143±10	0.490	143±10	2
37.892	64.86±5.03	0.80	71±6	0.470	71±6	1
40.382	162.98±7.35	3.87	170±8	0.380	168±8	1
40.593	253.39±8.03	2.40	283±10	0.370	282±10	1
40.715	145.81±6.02	1.02±0.30	170	0.370	170	1
41.260	80.33±6.11	0.15±0.02	170	0.360	170	1
41.855	270.87±9.06	4.80	144±6	0.350	143±6	2
42.689	457.08±17.64	175.59	458±18	0.348	397±18	1
43.657	251.41±8.71	4.29	267±10	0.390	265±10	1
44.991	426.96±13.68	16.97	438±14	0.425	431±14	1
45.882	453.29±12.47	2.00	293±10	0.370	293±10	2
46.175	45.82±9.35	.063±.018	170	0.375	170	1
46.225	207.51±10.89	1.2	126±12	0.380	126±12	2
46.708	103.95±5.29	0.268±.035	170	0.385	170	1
48.485	215.04±8.53	0.80	294±16	0.410	294±16	1
49.045	298.00±10.88	1.60	183±8	0.420	183±8	2
49.818	416.41±14.96	23.60	212±8	0.425	207±8	2
51.415	214.42±12.96	1.00	273±21	0.425	273±21	1
51.520	458.33±20.13	8.00	243±11	0.420	241±11	2
51.685	60.58±7.97	0.094±0.019	170	0.415	170	1
52.024	100.16±8.50	0.244±0.050	170	0.395	170	1
52.682	291.92±12.49	2.04	170±9	0.390	170±9	2
53.142	42.79±8.08	0.057±0.014	170	0.380	170	1
53.332	85.07±8.11	0.17±0.03	170	0.370	170	1
53.789	75.83±5.74	0.14±0.02	170	0.363	170	1
54.934	78.24±8.89	0.15±0.03	170	0.345	170	1
55.139	268.43±12.44	12.52	274±13	0.343	270±13	1
56.780	295.86±17.83	92.92	297±18	0.320	267±18	1

E_o (keV)	$\frac{g\Gamma_n(\Gamma_n + k\Gamma_n)}{\Gamma_n \gamma_{(meV)}}$	$g\Gamma_n$ (eV)	Γ_n (meV)	$k(10^{-3})$	$(\Gamma_n)_{eff}$ (meV)	g
57.610	56.72±9.63	0.085±0.022	170	0.310	170	1
57.745	337.53±15.49	2.0	203±11	0.310	203±11	2
58.500	166.44±12.15	0.5	250±27	0.300	250±27	1
59.600	274.44±12.68	3.94	148±9	0.294	147±9	2
60.552	165.27±11.04	4.34	172±12	0.290	171±12	1
61.064	300.70±13.47	10.34	155±8	0.275	154±8	2
61.800	61.69±6.72	0.097±0.017	170	0.270	170	1
62.932	334.54±14.42	12.00	172±8	0.260	170±8	2
63.473	161.56±10.46	0.66	107±20	0.255	107±20	2
63.635	237.72	1.00	156±22	0.250	156±22	2
64.841	372.68±21.25	145.09	374±21	0.249	338±21	1
65.554	118.59±8.59	0.39±0.09	170	0.248	170	1
65.987	41.74±7.47	0.055±0.013	170	0.247	170	1
67.454	379.43±39.53	14.36	195±22	0.244	193±22	2
67.677	66.40±32.12	0.9	72±37	0.243	72±37	1
67.810	62.25±35.74	1.80	65±38	0.243	65±38	1
67.999	487.75±73.41	180.00	489±74	0.243	445±74	1
69.109	172.46±31.19	0.50	263±73	0.238	263±73	1
69.896	132.96±31.17	1.24	149±39	0.237	149±39	1
70.065	79.50±35.98	0.15±0.12	170	0.237	170	1
70.160	300.73±42.35	2.00	177±30	0.236	177±30	2
70.630	464.58±44.61	3.00	275±40	0.236	275±40	2
71.135	222.55±40.53	1.00	143±40	0.236	143±40	2
72.077	174.37±48.81	10.80	177±50	0.236	174±50	1
72.588	228.30±50.80	1.0	296±85	0.237	296±85	1
72.998	352.76±57.01	2.0	214±55	0.237	214±55	2
75.473	169.77±14.09	1.50	191±18	0.242	191±18	1
75.720	274.03±16.71	2.00	159±14	0.242	159±14	2
76.685	779.03±36.00	260.71	781±36	0.243	718±36	1
77.162	40.02±16.94	0.052±0.029	170	0.245	170	1
77.300	418.30±23.86	3.00	243±20	0.246	243±20	2
77.830	159.91±14.29	3.00	168±16	0.246	167±16	1
78.430	155.91±16.57	1.88	170	0.248	170	1
78.850	122.90±14.13	2.22	130±16	0.249	129±16	1
79.113	24.34±13.50	0.028±0.018	170	0.249	170	1

E_o (keV)	$\frac{g\Gamma(\Gamma_n + k\Gamma_n)}{\Gamma_{\gamma}(\text{meV})}$	$g\Gamma_n$ (eV)	Γ_{γ} (meV)	$k(10^{-3})$	$(\Gamma_{\gamma})_{\text{eff}}$ (meV)	g
79.270	132.70±28.39	3.13	139±31	0.250	138±31	1
79.330	102.07±28.98	7.01	104±30	0.251	102±30	1
79.515	27.79	0.033±0.018	170	0.252	170	1
79.960	28.52±13.47	0.034±0.019	170	0.254	170	1
80.110	332.90±18.47	2.40	193±15	0.255	193±15	2
81.710	344.19±19.80	2.00	208±20	0.270	208±20	2
82.910	169.16±18.33	0.50	256±42	0.272	256±42	1
83.605	161.19±19.93	0.40	270±56	0.274	270±56	1
83.924	488.47±31.63	5.00	271±19	0.280	270±19	2
84.280	115.53±15.85	0.36±0.15	170	0.285	170	1
84.505	809.21±40.10	20.0	422±22	0.285	419±22	2
85.321	274.67±25.09	2.0	159±17	0.290	159±17	2
86.755	577.39±33.33	2.0	406±33	0.300	406±33	2
88.171	152.52±21.33	2.83	161±24	0.310	160±24	1
88.646	286.33±25.22	1.76	171±18	0.328	171±18	2
89.700	476.19±35.27	10.0	250±19	0.340	248±19	2
90.160	235.18±25.23	11.67	240±26	0.350	236±26	1
90.430	122.50±14.69	0.44±0.19	170	0.355	170	1
91.449	417.92±32.29	7.56	442±34	0.370	439±34	1
93.345	179.64±20.05	1.12	214±28	0.402	214±28	1
93.582	164.69±21.72	3.29	173±24	0.407	172±24	1
94.425	535.65±80.05	552.62	536±80	0.411	309±50	1
94.430	382.29±33.43	2.00	236±29	0.411	236±29	2
96.275	82.68±17.68	0.16±0.07	170	0.400	170	1
96.922	318.08±28.62	11.83	327±30	0.392	322±30	1
97.150	234.85±27.15	3.22	253±32	0.392	252±32	1
97.460	389.43±30.61	20.0	199±16	0.391	195±16	2
97.921	111.71±20.20	26.61	112±20	0.391	102±20	1
99.086	273.43±36.16	157.31	274±36	0.388	213±30	1
99.900	381.82±40.89	2.00	236±35	0.385	236±35	2
100.000	720.16±99.98	487.00	721±100	0.383	535±62	1
100.410	211.32±27.77	10.0	216±29	0.382	212±29	1
101.430	395.07±42.07	2.00	246±33	0.382	246±33	2
101.520	119.54±27.88	0.40±0.31	170	0.382	170	1
102.340	211.64±24.10	14.41	215±25	0.381	209±25	1

E_o (keV)	$\frac{g\Gamma_n(\Gamma_n + k\Gamma_Y)}{\Gamma}(\text{meV})$	$g\Gamma_n$ (eV)	Γ_Y (meV)	$k(10^{-3})$	$(\Gamma_Y)_{\text{eff}}$ (meV)	g
103.620	110.69±23.94	0.32±0.20	170	0.378	170	1
103.800	130.04±17.29	0.55±0.31	170	0.375	170	1
104.030	201.88±25.48	2.56	219±30	0.375	218±30	1
104.750	376.05±27.19	5.68	201±16	0.372	200±16	2
105.550	389.15±31.18	4.00	216±19	0.365	215±19	2
105.800	226.20±29.36	13.12	230±30	0.365	225±30	1
107.570	483.22±33.13	2.0	319±29	0.365	319±29	2
108.300	626.37±44.55	88.90	631±45	0.358	599±40	1
108.570	149.09±9.88	1.22±0.65	170	0.354	170	1
109.800	372.49±26.18	2.00	229±30	0.347	229±30	2
110.550	404.20±32.85	28.40	205±17	0.343	200±17	2
111.060	133.25±23.58	2.02	143±27	0.340	142±27	1
113.760	452.63±30.91	2.00	293±26	0.324	293±26	2
114.430	398.24±32.22	2.00	249±25	0.320	249±25	2
115.170	369.80±33.18	45.23	373±34	0.318	359±30	1
115.950	266.02±28.14	6.26	278±31	0.318	276±31	1
116.970	707.13±86.49	854.46	708±87	0.315	439±60	1
117.790	199.04±26.78	1.00	249±42	0.314	249±42	1
118.770	319.11±31.12	10.01	165±17	0.315	163±17	2
120.120	512.91±47.83	2.00	345±43	0.317	354±43	2
120.130	534.36±117.29	745.64	535±118	0.325	293±80	1
120.800	96.19±23.50	0.222±.125	170	0.330	170	1
121.170	272.63±27.82	2.00	158±21	0.330	158±21	2
122.020	319.26±31.46	11.60	164±17	0.340	162±17	2
123.000	503.35±34.61	2.00	336±31	0.340	336±31	2
123.380	152.46±7.34	1.48±0.69	170	0.340	169	1
124.510	424.48±34.27	3.00	247±23	0.335	246±23	2
125.050	395.67±32.70	3.24	225±21	0.330	224±21	2
125.550	265.15±33.57	3.0	145±20	0.320	144±20	2
127.100	263.39±39.13	2.0	152±30	0.300	152±30	2
127.260	373.71±47.85	5.80	200±27	0.285	199±27	2
127.470	188.19±36.31	0.830	243±61	0.280	243±61	1
127.770	357.35±32.88	4.20	195±20	0.280	194±20	2
128.510	888.22±50.95	150.47	894±52	0.274	853±52	1
129.280	417.34±33.47	20.00	213±18	0.260	210±18	2

$^{68}\text{Zn}(n,\gamma)$ Results

E_o (keV)	$\frac{g\Gamma(\Gamma+k\Gamma_n)}{n\Gamma_Y(\text{meV})}$	$g\Gamma_n$ (eV)	Γ_Y (meV)	$k(10^{-3})$	$(\Gamma_Y)_{\text{eff}}$ (meV)	g
3.801	58.9 $\pm$ 1.2	0.09	170	.793	170	1
5.044 $\pm$ 25	79.5 $\pm$ 2.8	0.15	170	.691	170	1
7.481	117.0 $\pm$ 1.5	0.40	83 $\pm$ 3	.565	83 $\pm$ 3	2
8.240	74.7 $\pm$ 1.5	0.133	170	.541	170	1
8.588	169.1 $\pm$ 2.4	1.0	203 $\pm$ 7	.528	202 $\pm$ 7	1
9.608	137.5 $\pm$ 2.3	0.72	0.170	.499	170	1
12.112	21.0 $\pm$ 1.3	0.024 $\pm$.002	168	.444	168	1
12.899	2.07 $\pm$ 0.80	0.002 $\pm$ 0.0008	170	.428	170	1
13.375	205.2 $\pm$ 5.4	20	207 $\pm$ 5	.425	198 $\pm$ 5	1
16.015	203.6 $\pm$ 4.8	7.0	210 $\pm$ 5	.394	207 $\pm$ 5	1
16.126	19.4 $\pm$ 1.7	0.022 $\pm$ 0.002	170	.393	170	1
18.055	59.8 $\pm$ 3.3	0.09	170	.378	170	1
18.400	167.0 $\pm$ 4.6	5.5	172 $\pm$ 5	.375	170 $\pm$ 5	1
18.815	5469 $\pm$ 15.9	308.0	548 $\pm$ 16	.372	433 $\pm$ 13	1
20.230	145.3	1.0	170	.366	170	1
20.966	153.6 $\pm$ 4.0	3.5	161 $\pm$ 4	.366	160 $\pm$ 4	1
22.843	85.8 $\pm$ 3.1	1.0	94 $\pm$ 4	.368	94 $\pm$ 4	1
24.741	285.9 $\pm$ 8.8	3.92	154 $\pm$ 5	.399	153 $\pm$ 5	2
25.907	44.6 $\pm$ 4.1	0.060 $\pm$ 0.008	170	.464	170	1
26.254	186.3 $\pm$ 7.7	3.41	197	.511	195 $\pm$ 8	1
26.504	254.6 $\pm$ 10.5	30	257 $\pm$ 11	.545	241 $\pm$ 11	1
27.335	44.9 $\pm$ 4.7	.060 $\pm$.009	170	.730	170	1
28.543	210.5 $\pm$ 9.2	4.02	222 $\pm$ 10	.786	219 $\pm$ 10	1
31.928	82.4 $\pm$ 7.4	.16	170	.620	170	1
32.763	79.8 $\pm$ 7.0	1.0	87 $\pm$ 8	.610	86 $\pm$ 8	1
33.507	256.3 $\pm$ 15.2	5.4	135 $\pm$ 8	.595	133 $\pm$ 8	2
34.416	120.3 $\pm$ 9.0	0.41	170	.578	170	1
34.710	244.0 $\pm$ 14.0	40.0	246 $\pm$ 14	.575	223 $\pm$ 14	1
36.743	163.5 $\pm$ 11.1	1.35	186 $\pm$ 12	.520	185 $\pm$ 12	1
36.857	161.5 $\pm$ 10.1	1.75	178 $\pm$ 10	.515	177 $\pm$ 10	1
37.007	81.5 $\pm$ 7.8	0.14	195 $\pm$ 10	.508	194 $\pm$ 10	1
37.886	92.4 $\pm$ 7.7	1.75	98 $\pm$ 8	.470	97 $\pm$ 8	1
39.270	187.9 $\pm$ 11.6	7.5	193 $\pm$ 12	.410	190 $\pm$ 12	1

E_o (keV)	$\frac{g\Gamma_n(\Gamma_n + k\Gamma_Y)}{\Gamma_n}(\text{meV})$	$g\Gamma_n$ (eV)	Γ_Y (meV)	$k(10^{-3})$	$(\Gamma_Y)_{\text{eff}}$ (meV)	g
41.792	63.5±7.9	0.09	216±14	.352	216±14	1
42.550	230.7±12.2	2.07	260±14	.348	259±14	1
44.563	66.6±7.5	0.110±0.020	170	.420	170	1
44.815	88.4±7.5	0.184±0.033	170	.424	170	1
45.214	63.0±5.0	0.1	170	.404	170	1
45.760	108.8±7.4	0.302±.057	170	.368	170	1
47.870	31.2±12.8	.038±.019	170	.390	170	1
48.000	263.8±46.1	106	265±46	.393	218±37	1
48.026	99.2±21.2	.238±.122	170	.395	170	1
48.230	46.2±9.4	.0634±.0177	170	.402	170	1
50.544	221.5±23.4	135.0	222±24	.442	162±18	1
50.680	55.1±5.6	.08	170	.442	170	1
50.933	237.7±16.5	0.8	169±17	.430	169±16	2
53.034	481.8±24.2	2.05	3.3±30	.380	312±30	2
53.893	220.1±17.2	5.0	230±25	.363	228±25	1
55.119	269.9±17.9	1.6	162±16	.343	162±16	2
55.238	47.5±11.7	.066±.023	170	.343	170	1
55.813	216.6±18.2	1.0	138±15	.337	138±15	2
56.695	293.6±23.1	30	297±30	.320	287±30	1
57.475	63.1±5.0	0.1	170	.310	170	1
57.560	221.5±36.0	175.0	222±36	.310	168±26	1
59.078	63.0±5.0	.1	170	.294	170	1
61.922	63.0±5.0	.1	170	.265	170	1
62.330	205.6±22.7	9.80	210±23	.260	207±23	1
62.787	315.4±24.0	10.0	230±25	.260	229±25	2
63.720	365.7±29.3	10.0	288±30	.250	287±30	2
64.668	351.2±27.0	2.0	213±25	.249	213±25	2
65.837	1664.9±104.3	1480	166.7±105	.247	1301±105	1
67.130	141.4±26.1	0.5	197±30	.243	197±30	1
68.917	126.9±10.0	0.5	170	.238	170	1
69.267	283.3±26.3	14.0	178±15	.237	177±15	2
70.900	265.2±29.8	17.06	269±30	.236	265±30	1
71.543	377.3±36.9	108.0	379±37	.236	353±35	1
74.612	338.1±23.8	1.6	214±20	.241	214±20	2
75.087	258.6±21.6	4.0	138±14	.241	137±14	2

E_o (keV)	$\frac{g\Gamma(\Gamma_n + k\Gamma_n)}{\Gamma_Y(\text{meV})}$	$g\Gamma_n$ (eV)	Γ_Y (meV)	$k(10^{-3})$	$(\Gamma_Y)_{\text{eff}}$ (meV)	g
75.568	307.3±30.3	204.0	308±30	.242	259±25	1
76.380	212.5±19.5	9.0	218±20	.243	216±20	1
77.104	441.1±28.5	6.0	238±23	.245	237±17	2
77.418	237.0±22.6	9.0	243±23	.247	241±23	1
78.331	91.9±8.0	0.2	170	.248	170	1
78.600	63.0±5.0	0.1	170	.249	170	1
80.759	312.6±29.1	27.24	158±14	.257	154±14	2
82.300	298.9±26.4	5.0	159±15	.270	158±15	2
82.784	108.5±9.0	0.3	170	.272	170	1
84.460	51.0±15.2	0.1	104±30	.285	104±30	1
85.670	180.5±20.3	2.37	195±17	.295	194±17	1
86.690	98.0	1.55	105±12	.306	104±12	1
86.960	99.6	3.86	102±12	.308	102±12	1
87.000	406.4±79.9	11.25	422±65	.310	419±65	1
87.290	99.2±0.8	1.0	110	.312	110±13	1
88.520	200.2±57.0	7.22	206±58	.328	204±58	1
90.225	83.1±36.5	0.4	105±45	.353	105±45	1
91.161	141.5±19.3	.845±.687	170	.367	170	1
93.370	119.0±33.1	.396±.367	170	.402	170	1
93.875	272.2±132.7	600.0	272±133	.410	26±13	1
93.880	81.6	.157	170	.410	170	1
94.463	137.0±23.4	.706±.620	170	.411	170	1
96.624	421.3±162.7	920	422±163	.397	57±22	1
96.806	126.9	.5	170	.396	170	1
97.882	216.4±55.7	5.0	226±61	.391	224±61	1
99.390	126.9	.5	170	.386	170	1
99.450	761.1±153.8	561.0	762±154	.386	545±100	1
99.675	91.9	.2	170	.385	170	1
101.750	166.0±51.4	1.0	199±60	.382	199±60	1
102.650	253.8±54.0	15.0	258±55	.380	252±55	1
102.870	292.3±57.5	4.0	158±35	.380	157±35	2
104.600	395.0±60.6	10.0	206±32	.373	204±32	2
105.670	434.3±65.1	140.0	436±66	.365	385±58	1
106.120	54.4	3.5	55 8	.363	54±8	1

E_o (keV)	$\frac{g\Gamma(\Gamma_\gamma + k\Gamma_n)}{\Gamma}(\text{meV})$	$g\Gamma_n$ (eV)	Γ_γ (meV)	$k(10^{-3})$	$(\Gamma_\gamma)_{\text{eff}}$ (meV)	g
108.780	403.4±71.8	2.0	253±40	.352	253±40	1
109.210	156.7	15.0	158	.348	153±30	1
110.270	1480.6±223.2	1730.0	1482±224	.344	887±150	1
111.610	160.9	3.0	170	.336	169	1
112.380	290.59	2.0	170	.333	170	2
112.660	281.2±60.4	2.0	164±30	.332	164±30	2
113.420	268.1±64.8	25.0	271±66	.326	263±64	1
116.920	103.4±73.6	1.0	115±74	.315	115±74	1
117.520	307.3±90.0	16.0	157±45	.314	154±45	2
118.540	106.9±73.5	75.46	107±74	.315	83±51	1
119.450	145.3±25.0	1.0	170	.317	170	1
122.570	189.4±82.2	57.0	190±82	.350	170±53	1
125.000	846.7±270.5	2295.0	847±271	.330	90±29	1
126.270	392.1±76.4	4.0	217±50	.309	216±50	2
127.320	219.1±60.5	2.0	246±76	.285	245±76	1
128.550	157.9±66.4	3.5	165±75	.274	164±75	1
129.340	196.4±70.0	2.0	218±86	.261	217±86	1
129.750	93.9±56.9	1.5	100	.256	100	1
130.090	90.3±49.4	13.69	91	.253	87	1
130.860	312.4±82.9	2.0	185±40	.247	185±40	2

using the HFBR fast chopper set up at the Brookhaven National Lab. Samples of enriched isotopes of Er_2O_3 wrapped in polyethylene bags were used as the capturing targets. The isotopic components of the samples are given in table IX.

The neutron energy region from epithermal to about 1 keV was covered by using different flight paths and variable channel widths.

In addition to the resonance capture, average capture measurements were also made using the filtered neutron beams of 2 and 24 keV. From a combination of the two sets of measurements average values of $\langle \Gamma_{\gamma ij} \rangle$ were obtained and from these the J^π assignments of low lying levels was made. These results were then used to compare the J^π assignments made by (d,p) and (d,t) work of Tøjm and Elbek. A comparison of the E1 and M1 transition strength was made with the theoretical predictions of single particle and giant dipole resonance estimates.

Table IX - Isotopic Abundance Of Erbium Isotopes

<u>^{164}Er</u>		<u>^{166}Er</u>	
A	% abundance	A	% abundance
162	<0.1	162	<0.02
164	67.19	164	<0.05
166	19.19	166	96.24
167	6.42	167	2.79
168	5.24	168	0.75
170	1.96	170	0.17

<u>^{168}Er</u>		<u>^{170}Er</u>	
A	% abundance	A	% abundance
162	<0.02	162	0.02
164	0.04	164	0.04
166	1.44	166	0.87
167	2.44	167	0.72
168	95.47	168	1.46
170	0.61	170	96.89

Contract Requirement

The principal investigator has fully complied with the proposed research plans outlined in his proposal. He has spent about 30% of his time on this project during the academic year and 100% time for the two summer months. He would continue to devote 30% of his time during the remainder of the contract period. A graduate student has spent 50% of her time for six months and a computer programmer has spent about 1 month on this project. In addition a visiting scientist has spent one year on this project.

PUBLICATIONS AND REPORTS

(April 1, 1974 to December 30, 1978)

1. U.N. Singh et. al. (Columbia), J.B. Garg (SUNYA), Neutron Resonance Spectroscopy: Magnesium, Phys. Rev. 10, 2150 (1974).
2. U.N. Singh et. al. (Columbia), J.B. Garg (SUNYA), Neutron Resonance Spectroscopy: Chlorine, Phys. Rev. 10, 2138 (1974).
3. U.N. Singh et. al. (Columbia), J.B. Garg (SUNYA), Neutron Resonance Spectroscopy: Fluorine, Phys. Rev. 10, 2147 (1974).
4. U.N. Singh et. al. (Columbia), J.B. Garg (SUNYA), Neutron Resonance Spectroscopy: Calcium, Phys. Rev. 10, 2143 (1974).
5. M. Pandey, J.B. Garg (SUNYA), N.N. Kaushal et. al. (R.P.I.), Capture and Total Cross Section Measurements on $^{54,58}\text{Fe}$ and ^{61}Ni , Linear Accelerator Project, Progress Report (January 1, 1974 - March 31, 1974).
6. J.B. Garg, (p, γ) Resonance Reaction, Proceedings of the Second International Symposium on Neutron Capture γ -ray Spectroscopy and Related Topics, September 2-6, 1974, The Netherlands, p. 401 ed. K. Abrahams et. al.
7. U.N. Singh et. al. (Columbia), J.B. Garg (SUNYA), Neutron Resonance Spectroscopy: Aluminum, Phys. Rev. 11, 1117 (1975).
8. M.S. Pandey, J.B. Garg (SUNYA), J.A. Harvey and W.M. Good (ORNL), High Resolution Total Cross Section in ^{63}Cu and ^{65}Cu , Bull. Am. Phys. Soc. 20, 561 (1975).
9. M.S. Pandey, J.B. Garg (SUNYA), J.A. Harvey and W.M. Good (ORNL), High Resolution Total Cross Section in ^{54}Fe and ^{56}Fe , Bull. Am. Phys. Soc. 20, 166 (1975).
10. M.S. Pandey, J.B. Garg (SUNYA), J.A. Harvey and W.M. Good (ORNL), Dependence of Level Spacing of the Isotopes of Fe Upon Parity, ORNL Physics Division Annual Report (1974).
11. J.B. Garg (SUNYA), R.E. Chrien and G.W. Cole (BNL), Resonance Neutron Capture Studies in ^{168}Er , Bull. Am. Phys. Soc. 20, 561 (1975).