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HIGH RESOLUTION NEUTRON TOTAL
CROSS SECTION MEASUREMENTS WITH
THE (A) ORNL LINAC AND (B) THE
COLUMBIA UNIVERSITY'S NEVIS
SYNCHROCYCLOTRON AND (C) WITH
B.N.L.HFBR.

Progress Report
for Period April 1, 1975 - March 31, 1976

J.B. Garg

Physics Department
State University of New York at Albany
Albany, New York 12222

December 1975

Prepared For

THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT NO. AT(11-1)-2439

MASTER

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ABSTRACT

The research work conducted under the AEC contract AT(11-1) 2439 involved the measurement, analysis and interpretation of high resolution neutron total and partial cross sections in the neutron energy range of few eV to few hundred keV in the following nuclei: Bi, Ta, Natural Copper, Natural Zinc, separated isotopes of copper, iron and zinc, e.g., ^{54}Fe , ^{56}Fe , ^{58}Fe , ^{63}Cu , ^{65}Cu , ^{64}Zn , ^{66}Zn , ^{67}Zn , ^{68}Zn , ^{70}Zn and Mn, Co, V. Some of these measurements were performed with the Columbia University's neutron velocity selector and the measurements on separated isotopes of iron, copper and zinc were performed with the Oak Ridge electron linear accelerator. By using area and shape analysis of resonances, the data were analyzed to extract the values of resonance parameters such as resonance energies (E_0), neutron widths (Γ_n), capture widths (Γ_γ) etc. The systematics of these results were investigated in detail. The results of these investigations have been submitted for publication in professional journals.

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I. INTRODUCTION

This technical progress report describes the collaborative research work carried out with various groups during the contract year (1975-76) on the high resolution measurements of neutron total and capture cross sections in certain nuclei of interest to the development of atomic energy. The first part deals with the work associated with the Columbia University's Nevis Accelerator. Here the main effort was directed toward the analysis and interpretation of the measurements in nuclei: Bi, Ta, natural copper, natural zinc, V, Mn and Co.

In the second part of the report the high resolution neutron cross section measurements in separated isotopes of iron, copper and zinc with Oak Ridge linear accelerator facility are described and in the third part collaborative efforts on the neutron capture γ -ray spectroscopy with the Brookhaven group is described.

During this period sufficient effort was also spent in converting and modifying various computer programs of data transfer, area and shape analysis from the IBM to the UNIVAC 1110 computer for the analysis of resonance parameters. We have now these programs available at Albany for data transfer, averaging of cross sections and for the analysis of data to extract resonance parameters and their analysis in terms of statistical theories.

The detailed accomplishment of the research work follows.

II. COLLABORATIVE PROGRAM WITH COLUMBIA UNIVERSITY

J.B. Garg (SUNYA), J. Rainwater, U.N. Singh, H. Liou and G. Hacken (Columbia University).

The high resolution neutron total cross section measurements made with the Nevis Synchrocyclotron with a 200 meter flight

path and a highly sophisticated data acquisition system with variable channel width over the last few years were analyzed using area analysis with Doppler broadening for resonances with narrow widths and using a multilevel R-matrix formalism for broad resonances. The information on the resonance energies, neutron widths and J^π assignments were made from this analysis. The values of average level spacing and strength function for $\ell = 0$ and $\ell = 1$ neutron scattering were determined. These informations are needed for the evaluation of the optical model potential parameters, as well as for the design of atomic reactors.

II(a) Neutron Resonance Spectroscopy ²⁰⁹Bi
J.B. Garg (SUNYA), U.N. Singh, J. Rainwater,
H.I. Liou and G. Hacken (Columbia University).

Neutron total cross section vs energy measurements were made for several thicknesses of bismuth metal. The results of the resonance parameter evaluation for 30 levels (12 s and 18 p) to 75 keV are given. Parameters for the p levels, and for 3 weak s-wave levels were determined using a transmission area analysis. An R-matrix multi-level shape analysis fitting was used to obtain the final resonance parameters for the 9 dominant $\ell = 0$ levels. The experimental points and R-matrix fit curve to 75 keV are shown. The (E_0, J, Γ_n) choices for these 9 levels are (0.800, 5, 4.6), (2.312, 4, 19.5), (5.112, 5, 5.4), (12.15, 4, 270), (15.54, 4, 118), (27.08, 4, 24), (33.34, 4, 240), (45.58, 5, 160), and (69.18, 5, 520), where E_0 is in keV and Γ_n is in eV. On the basis of these levels, we obtain for the s and p strength functions, $10^4 S_0 = (0.62 \pm 0.36)_{0.20}$

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and $10^4 S_1 = (0.13 \pm_{0.04}^{0.06})$. A channel radius of 9 fm was used to calculate S_1 and the evaluation ignores the possibility that some p levels were missed below 75 keV. The values of the resonance parameters are given in the Table I and II. A paper containing these results has been submitted to the Physical Review (see attached ^{pic.} reprint A).

II(b) Neutron Total Cross Sections In V, Mn and Co
J.B. Garg (SUNYA), R. Rainwater (Columbia Univ.).

The analysis of the total neutron cross section data on V, Mn and Co in the energy interval from 0 to 200 keV has been completed. The analysis performed using the R-matrix code, and the Harvey Atta's Code of area analysis provided values of the resonance parameters (E_0 , Γ_n , J^π).

A detailed and comprehensive investigation of the resonance parameters and the statistics of levels at excitation energy corresponding to the neutron binding energy was performed.

Making use of the thermal cross section data published in BNL Supl. II, the values of resonance parameters of the bound levels in these nuclei were also determined.

An investigation of the strength function obtained from these results was made in relation to the predictions of the optical model. The level density dependence on the J-value was also investigated. The results of this analysis would be published in scientific journals.

Table I. The R-matrix parameters for 9 observed, relatively strong, $l = 0$ levels in ^{209}Bi below 75 keV as plotted in Fig. 1. The s-wave potential scattering parameters (Ref. 7) $R_J^0 = A_J + B_J(E - E_{1/2})/E_{1/2}$ used $A_4 = -0.03$, $B_4 = 0.04$, $A_5 = -0.03$, $B_5 = 0.04$, with $E_{1/2} = 37$ keV and a channel radius $a = 9$ fm.

<u>E_0 (keV)</u>	<u>J</u>	<u>Γ_n (eV)</u>
0.800	5	4.6 ± 0.4
2.312	4	19.5 ± 1.0
5.112	5	5.4 ± 0.6
12.15	4	270 ± 45
15.54	4	118 ± 20
27.08	4	24 ± 6
33.34	4	240 ± 40
45.58	5	160 ± 30
69.18	5	520 ± 70

Table II. The parameters obtained using the transmission area analysis for 18 p levels and 3 weak s levels (denoted ‡) observed in the neutron interaction with ^{209}Bi to 75 keV.

<u>E_o (keV)</u>	<u>$g\Gamma_n$ (eV)</u>	<u>E_o (keV)</u>	<u>$g\Gamma_n$ (eV)</u>
3.348	0.08 ± 0.03	39.19	1.7 ± 0.5
4.455	0.12 ± 0.04	42.44	7 ± 2
6.524	0.28 ± 0.08	44.17	1.4 ± 0.4
9.018	0.16 ± 0.05	51.80	3.5 ± 1.0
9.153	0.12 ± 0.04	52.84‡	12 ± 3
9.762	0.11 ± 0.04	53.85‡	32 ± 8
17.45	0.50 ± 0.15	57.60	5.8 ± 1.5
21.05	2.5 ± 0.7	61.80‡	40 ± 8
25.28	9.5 ± 3.0	67.07	6.7 ± 2.0
29.23	3.0 ± 0.8	72.60	12 ± 4
37.25	6.3 ± 2.0		

II(c) Neutron Resonance Spectroscopy In Natural Copper-I
M.S. Pandey, J.B. Garg (SUNYA) and J. Rainwater
(Columbia University).

High resolution neutron total cross section in natural copper in the energy range 0-100 keV made with the Nevis Synchrocyclotron many years ago were analyzed with the help of a R-matrix program using UNIVAC 1110 Computer. The values of the resonance parameters (E_0 , Γ_n , S_0 , $\langle D \rangle$ etc., were determined from this analysis. For example for ^{63}Cu ; $S_0 = (2.05 \pm_{0.3}^{0.5})$ and for ^{65}Cu ; $S_0 = (1.19 \pm_{0.3}^{0.5})$ in units of $\text{eV}^{-1/2}$ were determined. The average spacings values are $\langle D \rangle = (2.38 \pm 0.38)$ keV for $J=1$ and $\langle D \rangle = (3.57 \pm 0.70)$ keV for $J=2$ resonances of ^{63}Cu . The corresponding values of ^{65}Cu are $\langle D \rangle = (4.17 \pm 0.88)$ keV for $J=1$ and $\langle D \rangle = (5.00 \pm 1.2)$ for $J=2$. By combining the thermal cross section data reported in BNL Suppl. II with our measurements we obtain the parameters of bound levels as well as the effective nuclear radius for the isotopes of copper. The values of the resonance parameters are given in the table.

A paper has been submitted to the Physical Review (see attached preprint B).

III. COLLABORATIVE RESEARCH WORK AT OAK RIDGE NATIONAL LAB.

J.B. Garg, M. S. Pandey (SUNYA), J.A. Harvey, W.M. Good
R.L. Macklin and J. Halpern (ORNL).

The measurement of neutron total and capture cross section in nuclei provide valuable data for reactor design, nucleosynthesis of elements, and for 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

Table I

$^{63}\text{Cu}(J=1)$			$^{63}\text{Cu}(J=2)$		
E_o (keV)	Γ_n (eV)	Γ_n^o (eV)	E_o (keV)	Γ_n (eV)	Γ_n^o (eV)
2.04 $\pm$ 0.01	41 $\pm$ 4	0.92	-0.30	4.19	0.24
2.65 $\pm$ 0.01	9 $\pm$ 1	0.17	0.580 $\pm$ 0.002	0.59 $\pm$ 0.02	0.024
4.86 $\pm$ 0.01	19 $\pm$ 2	0.27	5.39 $\pm$ 0.01	34 $\pm$ 4	0.50
7.56 $\pm$ 0.01	15 $\pm$ 3	0.17	5.82 $\pm$ 0.01	9 $\pm$ 1	0.11
			7.96 $\pm$ 0.01	60 $\pm$ 20	1.24
9.92 $\pm$ 0.02	105 $\pm$ 10	1.05			
12.52 $\pm$ 0.02	20 $\pm$ 4	0.18	9.19 $\pm$ 0.01	40 $\pm$ 4	0.42
13.70 $\pm$ 0.02	42 $\pm$ 5	0.36	10.84 $\pm$ 0.01	62 $\pm$ 6	0.60
15.09 $\pm$ 0.03	20 $\pm$ 4	0.16	13.16 $\pm$ 0.02	93 $\pm$ 10	0.81
15.82 $\pm$ 0.03	26 $\pm$ 5	0.21	17.86 $\pm$ 0.03	130 $\pm$ 30	0.97
16.31 $\pm$ 0.03	17 $\pm$ 3	0.13	21.00 $\pm$ 0.04	87 $\pm$ 10	0.60
18.12 $\pm$ 0.03	100 $\pm$ 30	0.74	22.79 $\pm$ 0.04	98 $\pm$ 10	0.65
21.24 $\pm$ 0.04	105 $\pm$ 15	0.72	24.91 $\pm$ 0.05	70 $\pm$ 7	0.44
25.78 $\pm$ 0.05	180 $\pm$ 100	1.12	36.12 $\pm$ 0.09	87 $\pm$ 10	0.46
26.61 $\pm$ 0.05	85 $\pm$ 30	0.52	36.86 $\pm$ 0.09	58 $\pm$ 8	0.30
29.53 $\pm$ 0.05	290 $\pm$ 50	1.69	42.00 $\pm$ 0.10	147 $\pm$ 20	0.72
31.40 $\pm$ 0.07	56 $\pm$ 10	0.32			
33.35 $\pm$ 0.08	356 $\pm$ 50	1.95			
37.97 $\pm$ 0.08	24 $\pm$ 5	0.12			
42.57 $\pm$ 0.09	265 $\pm$ 50	1.28			
44.71 $\pm$ 0.09	55 $\pm$ 10	0.26			
47.70 $\pm$ 0.09	23 $\pm$ 5	0.11			

Table II

$^{65}\text{Cu}(J=1)$ $E_o(\text{keV})$	$\Gamma_n(\text{eV})$	Γ_n^o	$^{65}\text{Cu}(J=2)$ $E_o(\text{keV})$	$\Gamma_n(\text{eV})$	Γ_n^o
0.230 $\pm$ 0.002	0.06 $\pm$ 0.02	0.004	-0.18	1.40	0.10
3.92 $\pm$ 0.01	24 $\pm$ 2	0.38	2.53 $\pm$ 0.01	25 $\pm$ 3	0.50
4.49 $\pm$ 0.01	11 $\pm$ 2	0.16	4.40 $\pm$ 0.01	8.6 $\pm$ 0.5	0.13
7.63 $\pm$ 0.01	26 $\pm$ 6	0.30	6.45 $\pm$ 0.02	17 $\pm$ 2	0.21
8.35 $\pm$ 0.01	15 $\pm$ 5	0.16	7.92 $\pm$ 0.02	80 $\pm$ 30	0.90
14.21 $\pm$ 0.02	45 $\pm$ 5	0.38	13.26 $\pm$ 0.03	33 $\pm$ 4	0.29
16.13 $\pm$ 0.03	50 $\pm$ 5	0.39	20.00 $\pm$ 0.04	136 $\pm$ 20	0.96
24.26 $\pm$ 0.05	109 $\pm$ 10	0.70	23.82 $\pm$ 0.05	58 $\pm$ 10	0.38
25.23 $\pm$ 0.05	150 $\pm$ 100	0.94	34.95 $\pm$ 0.09	209 $\pm$ 50	1.12
25.92 $\pm$ 0.05	30 $\pm$ 20	0.19	43.60 $\pm$ 0.01	128 $\pm$ 15	0.61
39.57 $\pm$ 0.09	342 $\pm$ 50	1.72	45.81 $\pm$ 0.12	70 $\pm$ 10	0.33
43.08 $\pm$ 0.09	210 $\pm$ 80	1.01			

Table III

E_o (keV)	E_o (keV)	E_o (keV)	E_o (keV)
0.650 $\pm$ 0.0009	14.560 $\pm$ 0.024	27.570 $\pm$ 0.063	37.250 $\pm$ 0.099
0.806 $\pm$ 0.001	16.610 $\pm$ 0.029	27.820 $\pm$ 0.064	40.200 $\pm$ 0.111
0.998 $\pm$ 0.001	16.760 $\pm$ 0.030	28.220 $\pm$ 0.065	40.600 $\pm$ 0.113
1.362 $\pm$ 0.002	19.380 $\pm$ 0.037	28.900 $\pm$ 0.068	41.000 $\pm$ 0.115
5.962 $\pm$ 0.006	21.770 $\pm$ 0.044	29.150 $\pm$ 0.069	41.670 $\pm$ 0.118
6.840 $\pm$ 0.007	22.040 $\pm$ 0.045	29.680 $\pm$ 0.071	43.750 $\pm$ 0.127
7.086 $\pm$ 0.008	23.300 $\pm$ 0.049	30.550 $\pm$ 0.074	44.150 $\pm$ 0.128
8.630 $\pm$ 0.011	23.650 $\pm$ 0.050	30.930 $\pm$ 0.075	46.700 $\pm$ 0.140
9.760 $\pm$ 0.013	25.590 $\pm$ 0.056	32.240 $\pm$ 0.080	48.900 $\pm$ 0.150
12.130 $\pm$ 0.018	26.960 $\pm$ 0.061	32.800 $\pm$ 0.082	49.500 $\pm$ 0.142
12.880 $\pm$ 0.020	27.220 $\pm$ 0.062	34.300 $\pm$ 0.088	

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, copper and zinc were undertaken for all these considerations and the fact that the ORELA neutron facility has the highest resolution for making such measurements up to few hundred keV neutron energy.

III(a) High Resolution Neutron Total Cross Section In $^{63}_{29}\text{Cu}$ and $^{65}_{29}\text{Cu}$. M.S. Pandey and J. B. Garg (SUNYA) and J.A. Harvey (ORNL).-II

High resolution neutron total cross sections in separated isotopes of copper have been measured using the ORELA neutron facility. From the area and shape analysis of the transmission and total cross section data precise values of the resonance parameters such as E_0 , Γ_n^0 , Γ_n^1 , J^π -values etc., have been determined. For example for ^{63}Cu , many s- and p-wave resonances have been observed from 10 to 150 keV giving a value of $\langle D \rangle_{J=2} = (4.00 \pm 0.50)$ keV, $\langle D \rangle_{J=1} = (2.74 \pm 0.28)$ keV, $\langle D \rangle_{J=1+2} = (1.63 \pm 0.13)$ keV, $S_{O_{J=1}} = (3.2 \pm 0.5) \times 10^{-4}$, $S_{O_{J=2}} = (2.3 \pm 0.35) \times 10^{-4}$, $S_{O_{J=1,2}} = (2.7 \pm 0.5) \times 10^{-4}$. For ^{65}Cu s and p-wave resonances were observed giving values of $\langle D \rangle_{J=1} = (3.59 \pm 0.42)$ keV, $\langle D \rangle_{J=2} = (5.19 \pm 0.73)$, $\langle D \rangle_{J=1+2} = (2.12 \pm 0.19)$ keV, $S_{O_{J=1}} = (3.1 \pm 0.6) \times 10^{-4}$, $S_{O_{J=2}} = (2.10 \pm 0.35) \times 10^{-4}$, $S_{O_{J=1,2}} = (2.60 \pm 0.5) \times 10^{-4}$. The detailed listing of the s and p-wave resonance parameters in the two isotopes are given in the following tables. A paper describing these results has been submitted to the Physical Review (see attached preprint C).

Table II

S-Wave Resonances

 ^{63}Cu ($J = 1$)

E_0 (eV)	$\Delta(E_0)$ (eV)	Γ_n (eV)	$\Delta(\Gamma_n)$ (eV)
12520.0	+ 50.0	12.0	+ 1.0
13695.0	+ 60.0	40.0	+ 2.0
15080.0	+ 70.0	29.0	+ 2.0
15805.0	+ 80.0	28.0	+ 3.0
16293.0	+ 50.0	23.0	+ 2.0
18110.0	+ 50.0	60.0	+ 5.0
21225.0	+ 75.0	123.0	+ 10.0
25800.0	+ 80.0	326.0	+ 30.0
26590.0	+ 50.0	129.0	+ 12.0
29500.0	+ 50.0	340.0	+ 30.0
30450.0	+ 50.0	23.0	+ 2.0
31390.0	+ 70.0	61.0	+ 6.0
33303.0	+ 80.0	289.0	+ 25.0
37930.0	+ 40.0	21.0	+ 2.0
40218.0	+ 50.0	11.0	+ 1.0
40585.0	+ 70.0	16.0	+ 1.5
42500.0	+ 60.0	315.0	+ 20.0
44750.0	+ 55.0	73.0	+ 7.0
47650.0	+ 55.0	52.0	+ 5.0
50250.0	+ 50.0	118.0	+ 10.0
53764.0	+ 60.0	648.0	+ 50.0
55380.0	+ 80.0	838.0	+ 80.0
57700.0	+ 90.0	13.0	+ 1.0
58410.0	+ 90.0	127.0	+ 10.0
59110.0	+ 90.0	54.0	+ 5.0
59900.0	+ 50.0	16.0	+ 1.5
63220.0	+ 50.0	106.0	+ 9.0
64970.0	+ 70.0	279.0	+ 15.0
66280.0	+ 80.0	329.0	+ 25.0
68860.0	+ 60.0	24.0	+ 2.0
69636.0	+ 40.0	237.0	+ 18.0
73728.0	+ 30.0	716.0	+ 60.0
74580.0	+ 80.0	115.0	+ 10.0
77953.0	+ 60.0	85.0	+ 7.0
79034.0	+ 45.0	204.0	+ 15.0
89677.0	+ 75.0	592.0	+ 50.0
92120.0	+ 20.0	176.0	+ 15.0
94649.9	+ 40.0	139.0	+ 11.0
102420.0	+ 40.0	169.0	+ 14.0
105050.0	+ 50.0	214.0	+ 20.0

Table II

S-Wave Resonances

 ^{63}Cu ($J = 1$)

(Continued)

E_0 (eV)	$\Delta(E_0)$ (eV)	Γ_n (eV)	$\Delta(\Gamma_n)$ (eV)
114850.0	+ 50.0	518.0	+ 40.0
116760.0	+ 60.0	90.0	+ 8.0
118250.0	+ 50.0	471.0	+ 40.0
120050.0	+100.0	201.0	+ 15.0
123920.0	+100.0	909.0	+ 75.0
125550.0	+ 95.0	607.0	+ 50.0
126850.0	+ 85.0	657.0	+ 55.0
129620.0	+ 50.0	247.0	+ 20.0
136820.0	+100.0	293.0	+ 25.0
137700.0	+ 90.0	31.0	+ 3.0
145110.0	+110.0	20.0	+ 2.0

Table III
S-Wave Resonance Parameters

^{63}Cu ($J = 2$)

E_0 (eV)	$\Delta(E_0)$ (eV)	Γ_n (eV)	$\Delta(\Gamma_n)$ (eV)
10839	+ 50	68.0	+ 2.0
13150	+ 50	93.0	+ 3.0
17855	+ 60	60.0	+ 5.0
21005	+ 75	91.0	+ 4.0
22790	+ 60	109.0	+ 5.0
24905	+ 50	66.0	+ 6.0
36135	+ 70	90.0	+ 6.0
36833	+ 75	91.0	+ 10.0
41980	+ 50	156.0	+ 10.0
54900	+ 50	293.0	+ 15.0
56300	+ 80	93.0	+ 10.0
59420	+ 65	16.0	+ 1.5
65300	+ 75	20.0	+ 1.0
72170	+ 70	81.0	+ 4.0
72790	+ 70	569.0	+ 20.0
75940	+ 50	17.0	+ 1.0
81440	+ 50	914.0	+ 30.0
89940	+ 50	7.0	+ 0.5
91276	+ 60	258.0	+ 18.0
95885	+ 60	200.0	+ 15.0
101320	+ 80	420.0	+ 20.0
103800	+ 70	339.0	+ 16.0
107400	+ 75	622.0	+ 30.0
108720	+ 75	478.0	+ 20.0
119580	+ 75	137.0	+ 9.0
128320	+ 70	736.0	+ 36.0
131230	+ 50	267.0	+ 17.0
133130	+ 60	385.0	+ 12.0
134030	+ 50	193.0	+ 9.0
135850	+ 60	826.0	+ 36.0
136800	+ 70	1014.0	+ 50.0
140480	+ 50	375.0	+ 15.0
141700	+ 80	317.0	+ 14.0
148350	+ 100	325.0	+ 12.0
149500	+ 100	346.0	+ 14.0

Table V

S-Wave Resonances

 ^{65}Cu ($J = 1$)

E_0 (eV)	$\Delta(E_0)$ (eV)	Γ_n (eV)	$\Delta(\Gamma_n)$ (eV)
14200.0	± 20.0	28.0	± 3.0
16100.0	± 50.0	40.0	± 5.0
17910.0	± 30.0	406.0	± 40.0
23802.0	± 30.0	31.0	± 2.0
24250.0	± 40.0	111.0	± 8.0
25185.0	± 25.0	167.0	± 10.0
25918.0	± 30.0	8.0	± 0.5
33414.0	± 40.0	48.0	± 4.0
39590.0	± 50.0	367.0	± 25.0
40970.0	± 60.0	72.0	± 6.0
43119.0	± 60.0	164.0	± 8.0
44184.0	± 50.0	50.0	± 5.0
47540.0	± 50.0	49.0	± 4.0
56351.0	± 40.0	59.0	± 5.0
57779.0	± 70.0	380.0	± 30.0
61980.0	± 70.0	236.0	± 20.0
65280.0	± 70.0	599.0	± 40.0
68099.0	± 80.0	303.0	± 20.0
73115.0	± 80.0	125.0	± 5.0
74540.0	± 40.0	1799.0	± 90.0
76075.0	± 70.0	175.0	± 50.0
82180.0	± 80.0	846.0	± 85.0
84067.0	± 70.0	245.0	± 24.0
89360.0	± 60.0	465.0	± 45.0
91207.0	± 80.0	38.0	± 4.0
94070.0	± 70.0	267.0	± 25.0
99245.0	± 50.0	855.0	± 9.0
101250.0	± 50.0	109.0	± 10.0
104600.0	± 60.0	90.0	± 10.0
111120.0	± 80.0	435.0	± 35.0
114140.0	± 40.0	223.0	± 20.0
116540.0	± 50.0	63.0	± 5.0
121630.0	± 30.0	690.0	± 70.0
123350.0	± 50.0	370.0	± 35.0
126550.0	± 100.0	469.0	± 50.0
133080.0	± 70.0	817.0	± 80.0
136350.0	± 50.0	24.0	± 2.0
139940.0	± 40.0	750.0	± 70.0
140870.0	± 100.0	82.0	± 5.0
143950.0	± 50.0	300.0	± 30.0

Table VI
S-Wave Resonances

^{65}Cu ($J = 2$)

E_0 (eV)	$\Delta(E_0)$ (eV)	Γ_n (eV)	$\Delta(\Gamma_n)$ (eV)
13240.0	+20.0	58.0	+ 5.0
20004.0	+ 40.0	93.0	+ 9.0
34240.0	+ 40.0	71.0	+ 5.0
34940.0	+ 40.0	185.0	+ 12.0
43765.0	+ 60.0	36.0	+ 3.0
45830.0	+ 30.0	42.0	+ 4.0
50412.0	+ 15.0	83.0	+ 8.0
53460.0	+ 60.0	104.0	+ 9.0
54362.0	+ 60.0	28.0	+ 2.0
54680.0	+ 70.0	25.0	+ 2.0
57130.0	+ 30.0	32.0	+ 3.0
64485.0	+ 70.0	134.0	+ 8.0
67140.0	+ 40.0	273.0	+ 15.0
69522.0	+ 25.0	243.0	+ 18.0
72685.0	+ 50.0	320.0	+ 25.0
78680.0	+ 70.0	159.0	+ 15.0
86300.0	+ 30.0	333.0	+ 30.0
98275.0	+ 70.0	331.0	+ 30.0
106980.0	+ 70.0	1293.0	+ 70.0
107300.0	+ 90.0	950.0	+ 80.0
117440.0	+ 85.0	587.0	+ 40.0
118990.0	+ 90.0	700.0	+ 60.0
123400.0	+100.0	833.0	+ 80.0
131860.0	+ 60.0	622.0	+ 50.0
135680.0	+ 80.0	1117.0	+100.0
149100.0	+100.0	509.0	+ 45.0

Table VI
S-Wave Resonances

^{65}Cu ($J = 2$)

E_0 (eV)	$\Delta(E_0)$ (eV)	Γ_n (eV)	$\Delta(\Gamma_n)$ (eV)
13240.0	+20.0	58.0	+ 5.0
20004.0	+ 40.0	93.0	+ 9.0
34240.0	+ 40.0	71.0	+ 5.0
34940.0	+ 40.0	185.0	+ 12.0
43765.0	+ 60.0	36.0	+ 3.0
45830.0	+ 30.0	42.0	+ 4.0
50412.0	+ 15.0	83.0	+ 8.0
53460.0	+ 60.0	104.0	+ 9.0
54362.0	+ 60.0	28.0	+ 2.0
54680.0	+ 70.0	25.0	+ 2.0
57130.0	+ 30.0	32.0	+ 3.0
64485.0	+ 70.0	134.0	+ 8.0
67140.0	+ 40.0	273.0	+ 15.0
69522.0	+ 25.0	243.0	+ 18.0
72685.0	+ 50.0	320.0	+ 25.0
78680.0	+ 70.0	159.0	+ 15.0
86300.0	+ 30.0	333.0	+ 30.0
98275.0	+ 70.0	331.0	+ 30.0
106980.0	+ 70.0	1293.0	+ 70.0
107300.0	+ 90.0	950.0	+ 80.0
117440.0	+ 85.0	587.0	+ 40.0
118990.0	+ 90.0	700.0	+ 60.0
123400.0	+100.0	833.0	+ 80.0
131860.0	+ 60.0	622.0	+ 50.0
135680.0	+ 80.0	1117.0	+100.0
149100.0	+100.0	509.0	+ 45.0

III(b) High Resolution Neutron Total Capture Cross Sections
In ^{63}Cu and ^{65}Cu , M.S. Pandey and J.B. Garg (SUNYA),
R. Macklin and J. Halperin (ORNL).-III

Neutron total capture cross sections in separated isotopes of copper (^{63}Cu and ^{65}Cu) from few keV to few hundreds of keV were measured using the ORELA facility. From these measurements the capture yields of resonances were accurately determined giving precise values of $g\Gamma_n$ and Γ_γ up to a maximum neutron energy of 50 keV. For ^{63}Cu one obtains a value of $\langle\Gamma_\gamma\rangle=(507\pm30)$ meV; and p-wave average level spacing $\langle D\rangle=(395\pm26)$ eV and strength function $S_1=(0.44\pm0.07)10^{-4}\text{eV}^{-1/2}$. For ^{65}Cu , one obtains a value for $\langle\Gamma_\gamma\rangle=(420\pm20)$ meV, $\langle D\rangle=(598\pm50)$ eV and $S_1=(0.47\pm0.08)\times10^{-4}\text{eV}^{-1/2}$. The corresponding s-wave mean level spacings for ^{63}Cu and ^{65}Cu are (1.04 ± 0.11) keV and (1.47 ± 0.19) keV respectively. A listing of the resonance parameters is given in the following table. A paper has been submitted to the Physical Review for publication (see attached preprint D).

Summary And Concluding Remarks Concerning Papers I, II & III

The present high resolution experiment on both neutron total cross-section and capture cross-section has helped to remove some of the ambiguities in the assignment of the angular momenta of the observed compound nucleus levels for ^{63}Cu and ^{65}Cu . Neutron capture measurement provided a larger number of p and possible d-wave resonances previously unreported. Higher resolution of the experimental facility used in the present work has helped remove some of the unresolved doublets, reported by the previous investigators, in both neutron total and capture cross-section measurement. An accurate determination of the capture yield under the p-wave

TABLE I

 $^{63}\text{Cu}(n,\gamma)$

E_0 (eV)	$\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}$ (meV)	$\Delta\frac{(g\Gamma_n\Gamma_\gamma)}{\Gamma}$ (meV)	Γ_γ (meV)	$\Delta(\Gamma_\gamma)$ (meV)	$g\Gamma_n$ (eV)	$\Delta(g\Gamma_n)$ (eV)	g (used for the fit)
3316.0	9.5	+ 0.11	500.0	+ 10.0	0.01	+ 0.001	0.375
3509.4	9.0	+ 0.10	500.0	+ 10.0	0.0095	+ 0.001	0.375
3818.5	1.8	+ 0.05	500.0	+ 8.0	0.0018	+ 0.0007	0.375
@ 4383.0	11.1	+ 0.6	500.0	+ 10.0	0.0118	+ 0.0006	0.375
@ 4406.0	218.7	+ 2.9	391.5	+ 5.8	2.06	+ 0.05	0.625
4445.3	14.6	+ 0.6	490.0	+ 5.0	0.0159	+ 0.0007	0.375
@ 4865.0	251.0	+ 2.0	700.0	+ 10.0	5.710	+ 0.500	0.375
5261.0	6.7	+ 0.3	400.0	+ 10.0	0.007	+ 0.001	0.375
5373.0	2.0	+ 1.0	350.0	+ 30.0	0.002	+ 0.001	0.375
+ 5402.2	356.7	+ 6.2	581.1	+ 10.3	20.0	+ 1.0	0.625
@ 5831.3	306.1	+ 5.8	519.0	+ 10.4	5.45	+ 0.50	0.625
6853.7	62.7	+ 1.8	500.0	+ 10.0	0.094	+ 0.004	0.375
7098.1	101.5	+ 2.6	500.0	+ 10.0	0.221	+ 0.012	0.375
@ 7576.7	228.7	+ 6.0	375.8	+ 10.2	8.69	+ 0.360	0.625
*+ 7963.0	536.8	+10.0	869.0	+ 30.0	46.1	+ 2.0	0.625
@ 8367.8	221.7	+ 5.9	634.6	+ 18.3	3.24	+ 0.13	0.375
8646.1	65.2	+ 3.2	500.0	+ 15.0	0.100	+ 0.009	0.375
8667.1	56.6	+ 3.2	500.0	+ 16.0	0.081	+ 0.006	0.375
+ 9216.0	229.2	+ 6.2	370.0	+ 12.0	25.2	+ 1.0	0.625
@ 9774.0	136.7	+ 5.8	383.8	+ 17.7	2.72	+ 0.17	0.375
*+ 9949.1	397.6	+12.0	1071.0	+ 33.0	40.0	+ 2.0	0.375
10332.0	68.4	+ 4.3	505.0	+ 87.1	0.107	+ 0.009	0.375
10566.0	7.0	+ 1.0	400.0	+ 8.0	0.008	+ 0.001	0.375
10651.0	10.9	+ 1.3	400.0	+ 8.0	0.011	+ 0.001	0.375
+10858.0	261.3	+ 6.7	420.9	+ 10.9	40.0	+ 2.0	0.625
*12525.0	170.0	+15.0	450.0	+ 20.0	0.91	+ 0.10	0.375
12911.0	134.7	+13.0	485.0	+ 90.6	0.52	+ 0.08	0.375
12973.0	45.2	+ 3.2	584.1	+197.1	0.057	+ 0.003	0.375
13078.0	23.0	+ 3.2	350.0	+ 5.0	0.027	+ 0.004	0.625
*+13178.0	386.2	+13.3	623.5	+ 21.7	43.0	+ 3.0	0.625
+13731.0	174.8	+ 9.1	284.7	+ 13.4	10.0	+ 1.0	0.625
14079.0	85.2	+ 4.8	469.8	+ 90.4	0.12	+ 0.01	0.625
14465.0	12.9	+ 1.4	450.0	+ 10.0	0.014	+ 0.002	0.375
14570.0	2.0	+ 2.0	450.0	+450.0	0.002	+ 0.002	0.375
14600.0	139.9	+ 0.6	244.0	+ 10.0	1.70	+ 0.09	0.625
@ 15118.0	151.4	+ 1.0	431.0	+ 10.0	2.4	+ 0.1	0.375
@ 15160.0	117.2	+ 0.9	330.0	+ 5.0	2.2	+ 0.1	0.375
* 15842.0	374.4	+15.0	580.0	+15.0	0.08	+ 0.01	0.625
15933.0	40.7	+ 2.0	580.0	+10.0	0.05	+ 0.01	0.375
@ 16108.0	172.2	+ 8.0	495.0	+ 5.0	2.38	+ 0.30	0.375
+ 16330.0	249.1	+10.0	710.0	+15.0	3.87	+ 0.40	0.375
16626.0	64.3	+ 3.2	207.0	+20.0	0.37	+ 0.01	0.375
17332.0	27.6	+ 0.5	540.0	+10.0	0.03	+ 0.01	0.375
17853.0	55.4	+ 7.3	550.0	+50.0	0.075	+ 0.014	0.375

TABLE I (cont.)

 $^{63}\text{Cu}(n,\gamma)$

E_0 (eV)	$\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}$ (meV)	$\Delta \frac{(g\Gamma_n\Gamma_\gamma)}{\Gamma}$ (meV)	Γ_γ (meV)	$\Delta(\Gamma_\gamma)$ (meV)	$g\Gamma_n$ (eV)	$\Delta(g\Gamma_n)$ (eV)	g (used for the fit)
*+ 17894.0	47.7	+ 6.6	550.0	+ 60.0	0.062	+ .011	0.375
17949.0	34.9	+ 5.7	550.0	+ 80.0	0.042	+ 0.008	0.375
18044.0	16.4	+10.0	500.0	+100.0	0.018	+ 0.02	0.375
+ 18121.0	173.5	+16.1	465.0	+ 43.4	34.0	+ 4.0	0.375
@ 18163.0	272.0	+16.3	750.0	+ 48.0	8.25	+ 0.75	0.375
18365.0	16.0	+ 3.6	500.0	+100.0	0.017	+ 0.004	0.375
19411.0	17.6	+ 2.9	350.0	+ 80.0	0.020	+ 0.004	0.375
19537.0	93.2	+ 6.7	264.0	+ 20.0	1.6	+ 0.4	0.375
19855.0	119.1	+ 7.3	340.0	+ 30.0	1.8	+ 0.3	0.375
20428.0	179.9	+12.5	530.0	+ 40.0	1.9	+ 0.4	0.375
20478.0	31.6	+10.0	500.0	+100.0	0.038	+ 0.01	0.375
20956.0	140.1	+16.0	405.0	+ 40.0	1.8	+ 0.5	0.375
+ 21050.0	402.2	+ 80	650.0	+ 80.0	40.0	+ 5.0	0.625
@ 21221.0	152.7	+ 15	420.0	+ 20.	5.0	+ 1.0	0.375
+ 21245.0	224.0	+50.0	600.0	+ 30.	50.0	+ 5.0	0.375
21267.0	18.4	+10.0	400.0	+ 17.	0.02	+ 0.01	0.375
21301.0	18.4	+10.0	400.0	+ 16.	0.02	+ 0.01	0.375
21559.0	101.6	+ 9.6	350.0	+ 12.	0.45	+ 0.05	0.375
21740.0	21.0	+10.5	350.0	+ 10.	0.02	+ 0.01	0.375
21780.0	183.9	+ 8.9	550.0	+ 20.	1.7	+ 0.5	0.375
22082.0	142.8	+10.0	421.0	+ 15.	1.5	+ 0.5	0.375
+ 22853.0	372.9	+50.0	600.0	+ 25.	67.0	+ 6.0	0.625
23129.0	39.2	+ 5.00	350.0	+ 10.	0.06	+ 0.01	0.375
23153.0	68.7	+ 7.00	340.0	+ 20.	0.149	+ 0.027	0.375
23337.0	173.6	+15.0	530.0	+ 15.	1.37	+ 0.2	0.375
23389.0	99.1	+ 6.00	540.0	+ 20.	0.194	+ 0.02	0.375
23550.0	30.7	+ 5.00	550.0	+ 15.	0.04	+ 0.01	0.375
@ 23663.0	260.8	+ 9.0	755.0	+ 10.	3.31	+ 0.5	0.375
23914.0	148.5	+ 5.0	465.0	+ 12.	1.00	+ 0.54	0.375
24334.0	26.9	+ 5.0	450.0	+ 10.	0.03	+ 0.01	0.375
24384.0	49.4	+ 4.5	500.0	+ 10.	0.07	+ 0.01	0.375
+ 24915.0	93.5	+10.5	250.0	+ 22.0	30.0	+ 1.5	0.375
24957.0	72.5	+ 8.5	220.0	+ 25.0	0.60	+ 0.10	0.375
24992.0	59.4	+ 5.4	500.0	+ 40.0	0.087	+ 0.005	0.375
25245.0	115.4	+14.0	500.0	+ 45.0	0.3	+ 0.1	0.375
25733.0	24.0	+ 6.0	450.0	+ 30.	0.03	+ 0.01	0.375
+ 25781.0	168.5	+10.0	450.0	+ 25.	120.0	+ 1.2	0.375
25816.0	131.5	+43.6	500.0	+ 42.	0.44	+ 0.30	0.375
@ 25975.0	331.5	+18.3	950.5	+ 85.5	4.75	+ 1.0	0.375
26102.0	59.5	+10.6	450.0	+ 40.0	0.092	+ 0.025	0.375
26469.0	83.4	+10.4	450.0	+ 35.0	0.165	+ 0.045	0.375
*+ 26666.0	414.4	+24.4	800.0	+ 67.0	36.6	+ 3.6	0.625
27060.0	78.0	+ 8.0	450.0	+ 30.0	0.15	+ 0.10	0.375
27253.0	128.4	+10.4	550.0	+ 35.0	0.34	+ 0.12	0.375

TABLE I (cont.)

 $^{63}\text{Cu}(n,\gamma)$

E_0	$\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}$	$\Delta \frac{(g\Gamma_n\Gamma_\gamma)}{\Gamma}$	Γ_γ	$\Delta(\Gamma_\gamma)$	$g\Gamma_n$	$\Delta(g\Gamma_n)$	g (used for the fit)
(eV)	(meV)	(meV)	(meV)	(meV)	(eV)	(eV)	
27915.	73.4	+ 5.4	450.0	+ 40.0	0.13	+ 0.10	0.375
28155.	64.7	+ 4.7	450.0	+ 30.0	0.11	+ 0.08	0.375
28677.	89.8	+ 6.8	450.0	+ 15.0	0.19	+ 0.03	0.375
28809.	31.7	+ 3.7	450.0	+ 5.0	0.04	+ 0.01	0.375
29150.	70.8	+ 7.4	450.0	+ 10.0	0.12	+ 0.02	0.375
29465.	29.5	+10.0	500.0	+ 30.0	0.035	+ 0.008	0.375
+ 29540.	399.4	+26.6	1067.9	+ 71.3	150.0	+10.0	0.375
30270.	41.9	+ 4.0	500.0	+ 25.0	0.05	+ 0.01	0.375
*@ 30541.	224.7	+14.1	639.0	+ 42.60	3.60	+ 0.40	0.375
30836.	27.3	+ 4.5	500.0	+ 15.0	0.032	+ 0.006	0.375
31232.	150.6	+15.	500.	+ 30.0	0.76	+ 0.03	0.375
31307.	74.4	+ 7.7	450.0	+ 20.0	0.133	+ 0.025	0.375
* 31433.	74.7	+ 8.4	450.0	+100.0	0.134	+ 0.027	0.375
31486.	128.6	+10.0	480.0	+ 60.0	0.45	+ 0.13	0.375
@ 32279.	278.4	+20.2	761.0	+ 56.5	11.4	+ 1.4	0.375
32408.	135.3	+12.6	463.0	+ 55.2	0.61	+ 0.10	0.375
32937.	149.3	+13.2	512.0	+ 58.1	0.67	+ 0.11	0.375
+ 33335.	485.6	+40.0	780.0	+ 35.0	125.0	+ 5.0	0.625
* 34135.	219.4	+19.6	723.0	+ 25.0	1.15	+ 0.54	0.375
@ 34347.	192.1	+19.5	543.0	+ 58.4	3.40	+ 0.60	0.375
@ 34527.	181.8	+21.3	514.0	+ 63.8	3.21	+ 0.50	0.375
34778.	61.8	+ 7.0	525.0	+484.2	0.09	+ 0.05	0.375
34850.	65.5	+10.0	450.0	+100.0	0.11	+ 0.05	0.375
35102.	39.8	+ 9.8	450.0	+ 50.0	0.05	+ 0.02	0.375
35335.	71.7	+ 7.5	550.0	+ 80.0	0.11	+ 0.05	0.375
35559.	67.3	+ 9.3	450.0	+ 50.0	0.11	+ 0.05	0.375
35843.	122.4	+15.9	420.0	+ 25.0	0.55	+ 0.10	0.375
+ 36139.	381.7	+20.0	612.0	+ 20.0	175.0	+15.0	0.625
36235.	73.1	+ 8.0	580.0	+ 50.0	0.11	+ 0.05	0.375
+ 36820.	239.3	+23.4	384.2	+ 37.6	69.8	+11.0	0.625
36930.	176.0	+10.0	550.0	+ 20.0	1.2	+ 0.1	0.375
37121.	9.1	+ 5.4	450.0	+ 50.0	0.009	+ 0.006	0.375
37978.	161.7	+10.7	470.0	+ 20.0	1.97	+ 0.40	0.375
38061.	122.2	+ 9.2	500.0	+ 70.0	0.35	+ 0.10	0.375
38467.	35.2	+13.7	430.0	+ 60.0	0.05	+ 0.02	0.375
38519.	84.6	+12.3	400.0	+ 50.0	0.19	+ 0.065	0.375
38769.	142.0	+10.0	460.0	+ 30.0	0.80	+ 0.20	0.375
*+ 39475.	503.0	+26.9	818.3	+ 44.8	30.4	+ 2.6	0.625
39842.	48.3	+ 8.3	500.0	+ 25.0	0.06	+ 0.01	0.375
* 40315.	352.1	+10.0	620.0	+ 50.	3.85	+ 0.50	0.625
40701.	209.6	+10.0	690.0	+ 45.	1.85	+ 0.4	0.375
41037.	141.4	+ 5.0	550.0	+ 40.	0.45	+ 0.01	0.375
41215.	45.5	+ 4.5	500.0	+ 50.	0.06	+ 0.01	0.375
41525.	31.0	+ 8.5	500.0	+ 50	0.037	+ 0.014	0.375
41735.	45.5	+ 4.5	500.0	+ 50.	0.006	+ 0.001	0.375

TABLE I (cont.)

 $^{63}\text{Cu}(n,\gamma)$

E_0	$\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}$	$\Delta\left(\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}\right)$	Γ_γ	$\Delta(\Gamma_\gamma)$	$g\Gamma_n$	$\Delta(g\Gamma_n)$	g (used for the fit)
(eV)	(meV)	(meV)	(meV)	(meV)	(eV)	(eV)	
+ 41990.0	406.0	+ 6.0	650.0	+ 60.	779.0	+130.0	0.625
42045.0	83.3	+10.3	500.0	+ 40.	0.150	+ 0.041	0.375
42225.0	165.4	+ 9.6	500.0	+ 40.	1.400	+ 0.50	0.375
42416.0	124.4	+13.7	500.0	+ 40.	0.37	+ 0.12	0.375
+ 42500.0	261.7	+ 0.1	700.0	+ 50.	87.5	+ 16.0	0.375
42647.0	178.6	+15.1	500.0	+ 35.	0.32	+ 0.05	0.375
43820.0	49.5	+12.4	450.0	+ 50.	0.07	+ 0.01	0.375
44000.0	147.9	+16.8	500.0	+ 40.	0.70	+ 0.35	0.375
@ 44158.0	225.4	+10.0	580.0	+ 50.	3.00	+ 1.0	0.375
44712.0	13.1	+ 9.2	450.0	+200.	0.014	+ 0.011	0.375
+ 44797.0	70.3	+47.0	189.5	+127.9	6.85	+ 1.00	0.375
44815.0	115.7	+42.4	500.0	+100.	0.30	+ 0.29	0.375
44885.0	65.2	+20.0	500.6	+442.3	0.10	+ 0.05	0.375
44926.0	55.1	+14.6	450.0	+200.	0.08	+ 0.03	0.375
45135.0	83.0	+11.5	400.0	+100.	0.79	+ 0.06	0.375
@ 45235.0	259.4	+29.1	730.9	+ 90.9	4.82	+ 0.68	0.375
45655.0	50.8	+16.8	500.0	+100.0	0.07	+ 0.03	0.375
45695.0	94.7	+18.0	500.0	+100.0	0.19	+ 0.07	0.375
45910.0	196.3	+16.2	540.1	+ 46.1	6.42	+ 0.79	0.375
46374.0	93.5	+11.5	442.2	+ 97.2	0.21	+ 0.06	0.375
@ 46696.0	248.0	+25.1	678.1	+ 70.5	10.0	+ 1.0	0.375
46725.0	108.6	+18.0	600.0	+ 80.0	0.21	+ 0.07	0.375
*@ 47510.0	485.6	+27.7	1387.3	+ 84.7	7.30	+ 0.84	0.375
47830.0	187.0	+ 5.0	550.0	+ 50.0	2.00	+ 0.20	0.375
47900.0	101.5	+14.5	455.8	+109.3	0.25	+ 0.07	0.375
48079.0	99.5	+11.5	450.0	+ 80.0	0.24	+ 0.06	0.375
@ 48324.0	210.3	+ 1.3	600.0	+ 70.0	3.22	+ 0.80	0.375
48405.0	81.7	+12.8	450.0	+100.0	0.16	+ 0.02	0.375
48745.0	126.0	+12.9	500.0	+ 50.0	0.38	+ 0.10	0.375
49468.0	107.3	+12.4	500.0	+ 60.0	0.25	+ 0.07	0.375
49502.0	11.5	+11.3	450.0	+300.	0.01	+ 0.01	0.375

+ s-wave identified

* possible multiplet or a doublet

@ l-assignment not possible -- not assigned to p-wave

TABLE II

 $^{65}\text{Cu}(n,\gamma)$

E_0	$\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}$	$\Delta \frac{(g\Gamma_n\Gamma_\gamma)}{\Gamma}$	Γ_γ	$\Delta(\Gamma_\gamma)$	$g\Gamma_n$	$\Delta(g\Gamma_n)$	g (used for the fit)
(eV)	(meV)	(meV)	(meV)	(meV)	(eV)	(eV)	
3142.8	3.8	+ 0.2	500.0	+100.0	0.0038	+ 0.0002	0.375
3594.4	21.4	+ 0.5	500.0	+ 50.0	0.0238	+ 0.0007	0.375
3754.3	1.4	+ 0.2	450.0	+ 20.0	0.0014	+ 0.0002	0.375
+ 3930.7	245.0	+ 2.9	671.7	+ 8.1	9.10	+ 0.50	0.375
+ 4496.2	149.8	+ 2.6	411.8	+ 7.5	4.98	+ 0.50	0.375
5858.0	11.4	+ 0.7	500.0	+ 30.0	0.0121	+ 0.0007	0.375
6167.0	4.4	+ 1.0	400.0	+ 20.0	0.0045	+ 0.001	0.375
6297.3	42.6	+ 3.0	450.0	+ 10.	0.057	+ 0.005	0.375
+ 6461.7	273.0	+ 6.0	443.2	+ 10.0	18.7	+ 0.66	0.625
6463.2	14.1	+10.0	600.0	+300.0	0.015	+ 0.001	0.375
6584.6	3.9	+ 1.0	450.0	+ 50.0	0.004	+ 0.001	0.375
6753.0	2.5	+ 1.0	450.0	+ 50.0	0.003	+ 0.001	0.375
7017.3	24.4	+ 2.0	500.0	+ 70.0	0.028	+ 0.005	0.375
+ 7638.0	123.3	+ 6.3	332.0	+ 30.0	12.8	+ 3.0	0.375
+ 7921.5	343.9	+ 7.6	553.2	+ 12.3	65.0	+ 5.0	0.625
8410.8	45.5	+ 1.7	550.0	+ 15.0	0.058	+ 0.003	0.375
9162.0	51.9	+ 2.0	500.0	+ 10.0	0.072	+ 0.004	0.375
9217.0	59.0	+ 2.3	550.0	+ 30.0	0.083	+ 0.005	0.375
9840.0	84.4	+ 3.0	550.0	+ 25.0	0.143	+ 0.008	0.375
11151.0	30.9	+ 0.6	500.0	+ 10.0	0.037	+ 0.004	0.375
12159.0	109.2	+ 4.6	520.0	+ 20.0	0.248	+ 0.024	0.375
+ 13265.0	233.2	+11.2	375.0	+ 10.0	45.0	+ 1.5	0.625
13299.0	36.3	+ 4.2	500.0	+ 20.0	0.045	+ 0.002	0.375
13706.0	79.2	+ 7.0	500.0	+ 20.0	0.14	+ 0.01	0.375
13827.0	7.5	+ 1.0	450.0	+ 30.0	0.008	+ 0.002	0.375
14107.0	53.8	+ 5.0	550.0	+ 20.0	0.07	+ 0.01	0.375
+ 14244.0	221.1	+20.0	600.0	+ 40.0	12.7	+ 1.0	0.375
14405.0	10.3	+ 1.25	450.0	+ 30.0	0.011	+ 0.001	0.375
+ 16177.0	147.8	+ 7.9	397.6	+ 21.3	28.7	+ 2.7	0.625
16288.0	1.5	+ 3.2	450.0	+ 20.0	.025	+ 0.004	0.375
16787.0	63.3	+ 3.0	550.0	+ 30.0	0.091	+ 0.005	0.375
17787.0	61.7	+ 4.9	450.0	+ 25.0	0.097	+ 0.012	0.375
+ 17910.0	310.1	+31.7	496.7	+ 50.7	268.0	+ 32.0	0.625
18028.0	92.9	+ 6.9	550.0	+ 60.0	0.169	+ 0.023	0.375
18372.0	24.7	+ 3.4	400.0	+ 20.0	0.029	+ 0.004	0.375
18892.0	27.6	+ 3.6	350.0	+ 22.0	0.035	+ 0.006	0.375
19412.0	116.0	+ 1.6	550.0	+ 20.0	0.26	+ 0.01	0.375
+ 20027.0	224.0	+ 0.1	600.0	+ 50.0	50.1	+ 4.0	0.375
20200.0	14.7	+ 2.5	500.0	+ 40.0	0.016	+ 0.003	0.375
20717.0	15.6	+ 2.8	500.0	+ 35.0	0.017	+ 0.003	0.375
21010.0	86.3	+ 4.5	550.0	+ 30.0	0.149	+ 0.013	0.375
@ 22089.0	118.9	+ 6.2	320.5	+ 16.9	11.0	+ 1.20	0.375
22257.0	21.8	+ 1.8	450.0	+ 30.0	0.025	+ 0.01	0.375

TABLE II (cont.)

⁶⁵Cu(n,γ)

E_0	$\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}$	$\Delta\frac{(g\Gamma_n\Gamma_\gamma)}{\Gamma}$	Γ_γ	$\Delta(\Gamma_\gamma)$	$g\Gamma_n$	$\Delta(g\Gamma_n)$	g (used for the fit)
(eV)	(meV)	(meV)	(meV)	(meV)	(eV)	(eV)	
22937.0	86.3	+ 4.0	500.0	+ 50.0	0.16	+ 0.05	0.375
23138.0	39.8	+ 4.0	450.0	+ 20.0	0.05	+ 0.01	0.375
23672.0	45.3	+ 4.3	450.0	+ 30.0	0.06	+ 0.01	0.375
+ 23868.0	173.8	+ 1.8	470.0	+ 30.0	12.3	+ 1.2	0.375
+ 24290.0	131.1	+13.2	351.1	+ 35.4	32.3	+ 6.0	0.375
@ 25223.0	131.8	+14.6	362.3	+ 42.3	4.43	+ 0.61	0.375
25315.0	101.0	+12.9	292.5	+ 42.6	1.27	+ 0.17	0.375
25814.0	62.8	+ 7.8	450.0	+ 20.0	0.10	+ 0.02	0.375
25991.0	138.3	+11.6	392.2	+ 34.9	2.33	+ 0.31	0.375
27025.0	43.0	+ 6.0	450.0	+ 30.0	0.058	+ 0.011	0.375
27856.0	27.0	+ 3.0	350.0	+ 30.0	0.034	+ 0.01	0.375
28087.0	93.9	+ 8.9	350.0	+ 30.0	0.33	+ 0.10	0.375
28296.0	142.8	+10.8	400.0	+ 50.0	2.96	+ 0.50	0.375
28797.0	103.7	+10.0	300.0	+ 25.0	1.33	+ 0.1	0.375
*@ 29274.0	206.8	+13.0	565.3	+ 36.4	8.50	+ 0.75	0.375
29647.0	38.8	+ 6.3	350.0	+ 20.0	0.06	+ 0.01	0.375
30827.0	103.5	+10.0	300.0	+ 25.0	1.3	+ 0.1	0.375
@ 30991.0	347.3	+21.3	566.0	+ 35.8	19.2	+ 1.8	0.625
32289.0	72.8	+ 7.3	320.0	+ 30.0	0.19	+ 0.05	0.375
@ 32535.0	188.9	+11.0	520.0	+ 20.0	6.0	+ 0.5	0.375
33516.0	108.1	+ 0.6	300.0	+ 19.2	2.75	+ 0.20	0.375
@ 33742.0	159.4	+ 0.5	440.0	+ 30.1	4.67	+ 0.44	0.375
+ 34240.0	93.5	+ 3.5	150.0	+ 10.0	43.8	+ 2.0	0.625
@ 34330.0	151.2	+12.1	420.0	+ 35.0	3.80	+ 0.50	0.375
34400.0	42.9	+ 5.9	400.0	+ 50.0	0.060	+ 0.016	0.375
34638.0	46.9	+ 6.9	450.0	+ 50.0	0.065	+ 0.015	0.375
+ 34991.0	291.1	+25.0	467.0	+ 39.7	117.0	+10.0	0.625
@ 35476.0	115.9	+ 7.5	320.0	+ 30.0	3.40	+ 0.5	0.375
36208.0	60.0	+10.0	320.0	+ 40.0	0.12	+ 0.03	0.375
36330.0	67.7	+ 7.7	300.0	+ 30.0	0.17	+ 0.05	0.375
@ 37221.0	145.4	+ 6.0	400.0	+ 20.0	4.75	+ 0.82	0.375
37868.0	82.2	+ 8.4	350.0	+ 30.0	0.22	+ 0.06	0.375
38410.0	75.7	+ 6.8	350.0	+ 30.0	0.18	+ 0.03	0.375
+ 39590.0	449.1	+43.7	1200.0	+100.0	230.0	+10.0	0.375
*@ 39610.0	302.8	+22.2	490.5	+ 36.3	25.0	+ 2.0	0.625
40210.0	77.6	+ 6.2	300.0	+ 20.0	0.25	+ 0.05	0.375
40750.0	159.3	+ 0.9	450.0	+ 20.0	2.85	+ 0.23	0.375
41097.0	142.3	+13.4	400.0	+ 35.0	2.78	+ 0.24	0.375
41690.0	158.8	+10.8	450.0	+ 20.0	2.70	+ 0.23	0.375
42754.0	90.6	+ 9.3	254.3	+ 27.4	1.80	+ 0.30	0.375
+ 43221.0	147.3	+15.9	394.0	+ 42.7	45.0	+ 5.0	0.375
43426.0	25.8	+ 7.5	70.7	+ 21.1	1.0	+ 0.5	0.375
43606.0	3.7	+ 7.7	10.0	+ 20.6	1.6	+ 0.7	0.375

TABLE II (cont.)

⁶⁵Cu(n,γ)

	E_0	$\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}$	$\Delta\left(\frac{g\Gamma_n\Gamma_\gamma}{\Gamma}\right)$	Γ_γ	$\Delta(\Gamma_\gamma)$	$g\Gamma_n$	$\Delta(g\Gamma_n)$	g (used for the fit)
	(eV)	(meV)	(meV)	(meV)	(meV)	(eV)	(eV)	
#	43736.0	130.0	+12.8	209.1	+20.7	22.5	+ 2.0	0.625
	43928.0	72.1	+ 9.0	212.7	+29.2	0.75	+ 0.20	0.375
#	44257.0	45.0	+19.3	120.1	+51.5	31.0	+ 5.0	0.375
	44336.0	92.0	+13.2	260.4	+39.8	1.6	+ 0.6	0.375
	44813.0	76.1	+ 8.5	214.5	+25.2	1.4	+ 0.35	0.375
	44930.0	42.6	+ 6.6	120.5	+19.8	0.75	+ 0.15	0.375
	45526.0	76.3	+10.0	226.5	+33.2	0.75	+ 0.25	0.375
#	45762.0	124.0	+14.3	199.3	+23.1	26.6	+ 4.2	0.625
@	45934.0	278.0	+21.1	796.7	+65.1	4.0	+ 1.0	0.375
	46275.0	57.8	+10.0	160.0	+28.8	1.6	+ 0.5	0.375
	47246.0	217.9	+29.2	652.0	+98.0	2.0	+ 0.7	0.375
	47375.0	70.0	+30.0	350.0	+20.0	0.15	+ 0.05	0.375
#	47640.0	137.7	+17.0	370.0	+30.0	18.3	+ 2.0	0.375
	47865.0	125.0	+20.0	400.0	+20.0	0.75	+ 0.10	0.375
	48983.0	169.4	+25.3	534.0	+24.0	1.1	+ 0.5	0.375
	49752.0	178.1	+29.0	578.0	+30.0	1.0	+ 0.5	0.375
	50107.0	138.2	+22.1	440.0	+25.0	0.85	+ 0.40	0.375
+	50342.0	68.7	+25.5	110.0	+40.0	50.6	+ 5.0	0.625
	50535.0	93.1	+20.7	350.0	+25.0	0.32	+ 0.1	0.375
	50926.0	74.1	+15.6	350.0	+30.0	0.17	+ 0.05	0.375

+ s-wave identified

* possible multiplet or a doublet

@ ℓ -assignment not possible -- not assigned to p-wave

occurrence of both s- and p-wave level

resonances was possible because all the s-wave resonances present in the neutron-capture data which were not very well resolved on account of large self-protection effect were readily available for capture data analysis from the analysis of the complementary neutron total cross-section data. There is, however, a difficulty experienced in determining the accurate value of $g\Gamma_n$ for some of the very weak resonances for which $g\Gamma_n$ was significantly smaller than the instrumental resolution. As a result, an underestimation in the $g\Gamma_n$ values of these resonances occurred which is exhibited by the comparison of the experimental set of reduced neutron widths with that predicted by the Porter-Thomas reduced neutron width distribution. Self-protection effect is not appreciable for weak s-wave resonances, some of which were attributed to p-wave neutron interaction in the initial analysis of the capture data. Statistical studies of the parameters and the determination of the values of the strength function made it evident that some of these be attributed to s-wave neutron interaction.

The nuclei in this work lie near the shoulder of strength function maxima of both s- and p-wave neutron interaction predicted by the optical model. The experimentally determined values of the strength function were reproduced by optical model calculations with the assumption of the spherical potential. These optical parameters were also tested to reproduce reasonable strength function values for the other mass numbers between 47 and 70. A large number of observed s- and p-wave resonances impart high degree of statistical accuracy to the values of the average level spacing $\langle D \rangle$ and s- and p-wave strength functions S_0 and S_1 , respectively. The calculated values of the strength function were found to depend

very sensitively on incident neutron energy, the real part of the potential V_0 and the diffuseness parameter for the potential form factor in the optical model.

The following concluding remarks can be made:

1. For neutron capture measurement in $^{63,65}\text{Cu}$, a large number of hitherto unreported resonances is observed and the resonance parameters deduced. This provides quite an accurate value of the p-wave strength function and the average level spacing $\langle D \rangle$ although the possibility that some of the resonances belong to $\ell=2$ capture can not be ruled out with complete certainty. For neutron energy between (20-50) keV the results from the present work form the only reliable source of capture resonance parameters available.

2. For neutron total cross-section measurement in $^{63,65}\text{Cu}$ a thoroughly new set of spin assignment and angular momenta assignment is done. A careful analysis combining the "area analysis" results and the "R-matrix analysis" results leave small room for ambiguities in these assignments. Some of the doublets not properly resolved previously are well resolved in the present work. This helped to determine a more accurate value of $\langle D \rangle_{\ell=0}$ and S_0 for different spin states involved. However it seems apparent that even the highest energy resolution total cross section data is not adequate to observe the complete sequence of p-wave levels. A complementary measurement of total capture cross section is essential for an estimation of the average properties of p-wave levels.

The present measurements of total and capture cross section in the isotopes of copper performed using the same neutron facility has clearly demonstrated the usefulness of such combined measurements in determining the average properties of neutron resonance parameters in nuclei.

III(c) High Resolution Total Neutron Cross Section in ^{54}Fe and ^{56}Fe . M.S. Pandey, J.B. Garg (SUNYA) and J.A. Harvey and W.M. Good (ORNL).

The analysis of high resolution neutron total cross sections on separated isotopes of iron: ^{54}Fe , ^{56}Fe , made earlier with the ORELA facility has been completed and the results of this analysis were presented at the conference on Neutron Cross Section Technology held at Washington. The attached preprint(E) will be published in the proceedings of this conference. The values of the resonance parameters such as E_0 , Γ_n , S_ℓ , $\langle D \rangle$ were obtained and a study of the statistical distribution of average parameters was made in comparison with the theoretical predictions (see attached preprint E).

III(d) High Resolution Total Neutron Cross Section in ^{58}Fe and ^{57}Fe . J.B. Garg (SUNYA) and J.A. Harvey (ORNL).

The total cross section data in these nuclei is currently being analyzed to extract the resonance parameters and it is anticipated that the analysis would be completed during the contract year.

III(e) Total Capture Cross Section in Manganese

The total capture cross section in Mn has been measured with ORELA facilities. This data is being analyzed at Albany using the LIFSIT program on UNIVAC 1110. The analysis of this data would provide important information about the resonance para-

meters of p and d-wave level sequence. This information is not available from total cross section data reported earlier.

III(f) Total Cross Section in Zn Isotopes
J.B. Garg (SUNYA), J.A. Harvey (ORNL)

The total cross section measurements in the zinc isotopes (^{64}Zn , ^{66}Zn , ^{67}Zn , ^{68}Zn , and ^{70}Zn) were performed in the energy range of few keV to few hundred keV during a two week run with ORELA during July, 75. The raw data has been processed for normalization, dead time and back ground correction and the transmission and cross section values have been calculated. For these measurements two sample thicknesses (thick and thin) were used for most of the isotopes. In addition their natural sample measurements were also performed.

This data would be analyzed for resonance parameters using area and shape analysis during the remainder of the contract period.

IV. Resonance Neutron Capture γ -Rays From ^{168}Er .
J.B. Garg (SUNYA), G.W. Cole, H.I. Liou,
R.E. Chrien (Brookhaven National Lab.)

Gamma rays following neutron capture in 7 major s-wave resonances in ^{168}Er up to 1 keV have been measured. The results serve to confirm and extend the knowledge of levels in ^{169}Er obtained from previous (d,p), (d,t) and thermal (n, γ) experiments. Absolute width determinations are made and a photon strength function is obtained. The following tables lists the gamma ray energies and the absolute values of the partial radiative widths (The preprint of the paper to be published in the Physical Review is attached-F).

TABLE I. The partial widths for radiative transitions from 7 resonances in ^{168}Er are shown in this table.

A number of entries show upper limits only, indicating non-observance for that transition. In the last column the quantity $\langle \Gamma_{\gamma f} \rangle_{\lambda} (B_N/E_{\gamma})^3$ is shown. This represents the partial width evaluated at the neutron binding energy (B_n) by correcting the E_{γ}^3 phase-space factor for photon emission.

E_{γ} (keV)	E_x (keV)	$E_n=1005$ eV		$E_n=830$ eV		$E_n=527$ eV		$E_n=312$ eV		$E_n=244$ eV		$E_n=189$ eV		$E_n=79$ eV		$\langle \Gamma_{\gamma f} \rangle$ (meV)
		$\Gamma_{\gamma\lambda f}$	$\Delta\Gamma_{\gamma\lambda f}$	$\Gamma_{\gamma\lambda f}$	$\Delta\Gamma_{\gamma\lambda f}$	$\Gamma_{\gamma\lambda f}$	$\Delta\Gamma_{\gamma\lambda f}$	$\Gamma_{\gamma\lambda f}$	$\Delta\Gamma_{\gamma\lambda f}$	$\Gamma_{\gamma\lambda f}$	$\Delta\Gamma_{\gamma\lambda f}$	$\Gamma_{\gamma\lambda f}$	$\Delta\Gamma_{\gamma\lambda f}$	$\Gamma_{\gamma\lambda f}$	$\Delta\Gamma_{\gamma\lambda f}$	
		(meV)		(meV)		(meV)		(meV)		(meV)		(meV)		(meV)		
6003.0	0	<0.3		<0.3		1.45	.31	10.05	.47	<0.2		<0.2		<0.2		1.64
5939.0	64.0	4.40	.51	<0.5		0.98	.24	1.09	.31	<0.2	1.20	.16		<0.2		1.13
5441.5	562.4	0.55	.24	1.73	.31	0.65	.24	0.39	.16	<0.2	2.12	.24	0.72	.16		1.18
5404.0	599.0	1.19	.47	<0.5		6.22	.94	0.92	.31	0.42	.16	1.87	.31	<0.6		2.08
5289.0	714.0	0.98	.39	1.07	.31	1.21	.31	2.09	.24	3.07	.31	<0.2		<0.1		1.76
5143.9	859.1	<0.6		0.77	.24	<0.6		<0.2		<0.2		<0.2	0.65	.16		0.32
4950.0	1053.0	0.68	.24	<0.2		1.42	.16	<0.2		<0.3	0.32	.12	5.82	.31		2.22
4923.5	1079.5	0.8	0.3	1.0	0.4	0.5	0.2	0.5	0.2	<0.2		<0.2	<0.2			0.57
4910.0	1093.0	<0.4		0.90	.31	1.34	.16	<0.4		<0.3	0.67	.24	1.72	.20		1.21
4617.0	1386.0	2.31	.47	1.81	.20	1.11	.31	<0.2		<0.2		<0.2	<0.2			1.64
4533.3	1469.7	<0.6		<0.3		0.57	.16	<0.2	0.29	.08	0.65	.16	0.26	.08		0.58
4516.2	1486.8	<0.6		<0.3		2.47	.47	<0.2		<0.2	0.36	.12	0.57	.12		1.15
4473.3	1529.7	<0.5		<0.3		1.69	.47	0.42	.16	<0.2	0.57	.12	0.31	.08		1.03
4449.0	1554.0	<0.6		<0.6		0.73	.31	<0.3	0.39	.12	1.16	.24	0.61	.16		1.02
4430.8	1572.2	<0.6		<0.6		0.53	.31	<0.3	0.45	.15	1.30	.25	<0.2			0.82
4181.6	1821.4	<0.6		0.65	.19	1.00	.39	<0.3	0.37	.12	<0.2		<0.2			0.85

TABLE I. (Cont.)

E_Y (keV)	E_X (keV)	$E_n=1005$ eV		$E_n=830$ eV		$E_n=527$ eV		$E_n=312$ eV		$E_n=244$ eV		$E_n=189$ eV		$E_n=79$ eV		$\langle \Gamma_{Yf} \rangle$ (meV)
		$\Gamma_{Y\lambda f}$ (meV)	$\Delta \Gamma_{Y\lambda f}$	$\Gamma_{Y\lambda f}$ (meV)	$\Delta \Gamma_{Y\lambda f}$	$\Gamma_{Y\lambda f}$ (meV)	$\Delta \Gamma_{Y\lambda f}$	$\Gamma_{Y\lambda f}$ (meV)	$\Delta \Gamma_{Y\lambda f}$	$\Gamma_{Y\lambda f}$ (meV)	$\Delta \Gamma_{Y\lambda f}$	$\Gamma_{Y\lambda f}$ (meV)	$\Delta \Gamma_{Y\lambda f}$	$\Gamma_{Y\lambda f}$ (meV)	$\Delta \Gamma_{Y\lambda f}$	
4163.6	1839.4		<0.6		<0.3	1.04	.31		<0.3	0.25	.08	0.31	.12	0.52	.16	0.91
4154.7	1848.3	0.91	.24		<0.2	1.13	.31		<0.3	0.83	.16	0.35	.12		<0.2	1.38
4134.9	1868.1	0.61	.24		<0.3		<0.5		<0.3	0.48	.16	0.42	.12		<0.2	0.66
4073.8	1929.2		<0.4	1.29	.31	0.91	.24		<0.3	0.28	.08		<0.2	1.12	.12	1.64
4055.5	1947.5		<0.6	1.53	.39		<0.5		<0.3		<0.2		<0.2	0.82	.16	1.09
4047.6	1955.4		<0.5	0.55	.16	1.21	.47	0.57	.16		<0.3		<0.3		<0.2	1.09
3980.2	2012.8	0.82	.24	0.69	.20	2.50	.63	0.98	.24		<0.2		<0.3	3.53	.39	4.19*
3973.5	2029.5	1.09	.31	0.57	.16	1.57	.47		<0.2		<0.3		<0.5	1.26	.24	2.21
3878.9	2124.1	0.72	.31		<0.5		<0.5		<0.3	0.81	.24	0.50	.12		<0.2	1.07
3864.0	2139.0		<0.4		<0.3		<0.5	0.69	.20		<0.2	0.68	.12	0.20	.08	0.84
3838.0	2165.0		<0.5		<0.3	0.75	.28	0.50	.20	1.28	.24		<0.2	0.22	.08	1.50
3823.0	2180.0	0.56	.24		<0.3	0.97	.31		<0.3	1.81	.31		<0.2		<0.2	1.84
3780.6	2222.4	0.61	.24		<0.3	0.92	.31		<0.3	0.27	.08	0.61	.24	0.73	.16	1.80

* Possibly a doublet.

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 current term. A graduate student has spent 100% of his time on the research.

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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).
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