NEUTRON CROSS SECTIONS
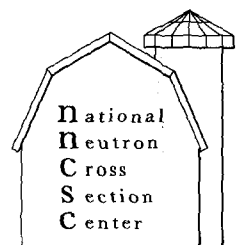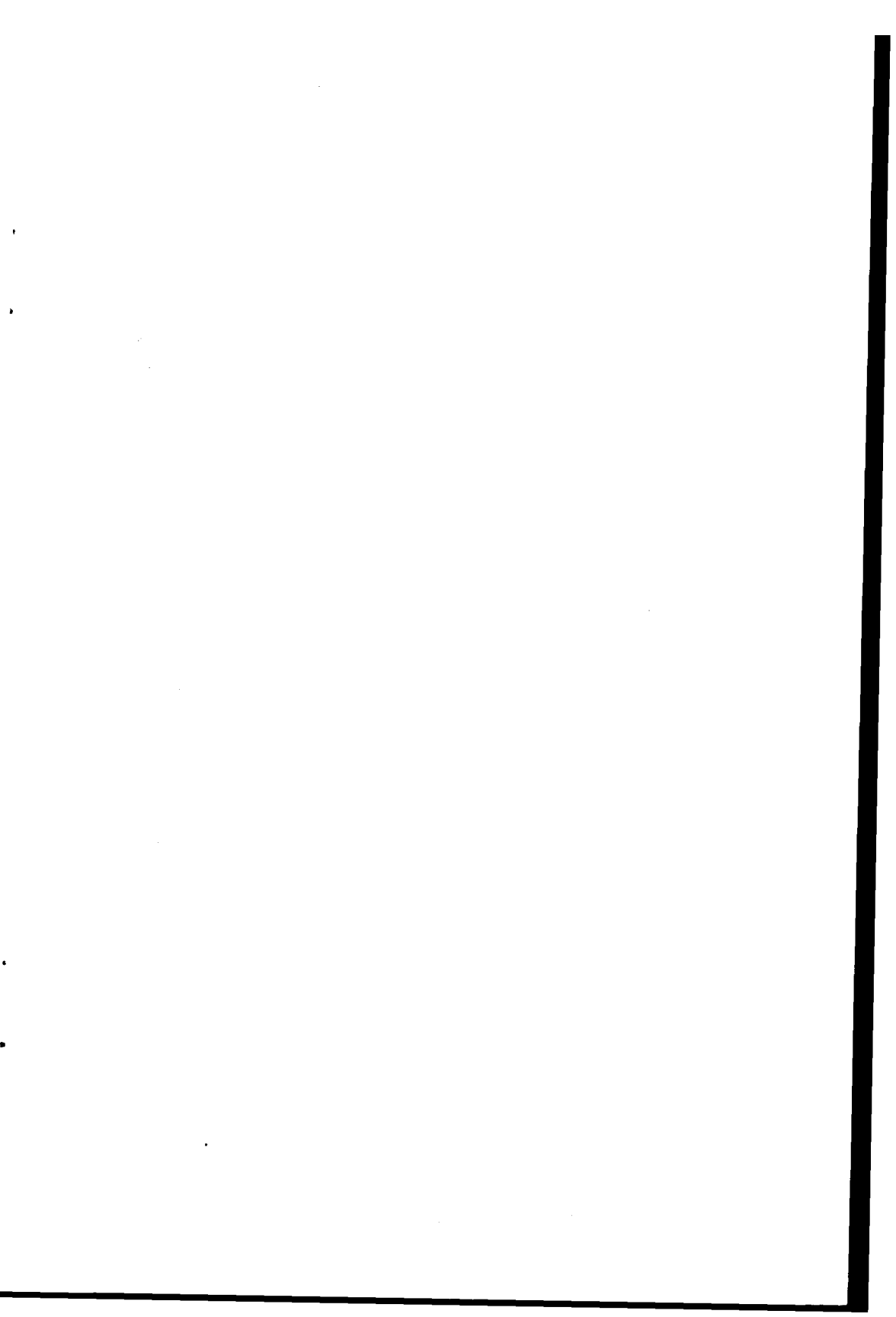# OF ^{59}Co BELOW 100 keV

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NEUTRON CROSS SECTIONS OF ^{59}Co BELOW 100 keV

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Neutron Cross Sections of

^{59}Co Below 100 keV

I.   Introduction

The importance of ^{59}Co stems from its use as a structural

material in nuclear technology and a standard in thermal cross

section measurements. Below a neutron energy of about 1 eV the

thermal cross section behaves as 1/v. In addition, its absorp-

tion resonance integral is becoming increasingly well known to

warrant its adoption as a standard. The first resonance at 132

eV is a strongly scattering resonance, which property makes it

suitable for producing a 132 eV "momoenergetic" beam from reactor

spectrums[1]. Furthermore ^{59}Co lies in a mass region where the

3s-wave strength function reaches its maximum value, which fact

makes it a candidate for the study of direct capture[2] component

of the reaction mechanism. For this to be possible, an accurate

knowledge of the resonance parameters of ^{59}Co is necessary. In

particular, the resonance parameters of a bound level should be

well determined and the questions of a possible bound level with

spin and parity 4$^-$ should be settled since it is crucial for

analysis of the capture spectra data.

The present ENDF/B IV evaluation of ^{59}Co consist of two

parts. The first part below 100 keV, carried out at BNL, deals

with the representation of the total, scattering, and capture

cross sections in terms of Breit-Wigner multilevel resonance pa-

rameters. The second part[3], carried out at ANL concerns itself

with the evaluation (and in most instances measurements) in the
energy range 0.1 – 20 MeV. In this report we present the analy-
sis, evaluation, and documentation of the data below 100 keV.

The present evaluation differs basically from the previous
ENDF/B III (MAT 1118) (in the resonance region) in the following
respects: (1) the resonance energy region have been extended
from 35 keV to 100 keV, (2) to describe the thermal capture,
scattering, total cross section and the polairzation data single
s-wave bound level with spin 3 was invoked. In the previous
evaluation two bound levels with respective spins 3 and 4 were
used. The necessity to invoke in ENDF/B III a bound level with
spin 4 is attributed to adoption of a radiative width of 0.4 eV
for the resonance at 132 eV with spin 4. The present evaluation
adopts a radiative width of 0.48 eV for this resonance, i.e. as
recommended in BNL 325 (1973).

Above neutron energy of 100 keV, the differences between
ENDF/B IV and ENDF/B III are well described by Guenther et al[3].

II.   Thermal and Low Energy Cross Sections

The experimental data below a neutron energy of 100 eV are scarce. At the time of the evaluation, two data sets were available. The total cross section of ^{59}Co in the energy range 0.03 – 1.0 eV was measured by Bernstein et al[5] using a crystal spectrometer. The useful energy range of the spectrometer is 0.03 – 0.7 eV. At lower energy limit, the instrument suffers from higher order contamination while at the higher end, neutron background increases sharply. The data were fitted[5] by the technique of least squares to obtain

$$\sigma_t(E) = (5.0 \pm 0.5) + (6.1 \pm 0.1) \ E^{-1/2} \quad barns$$

Employing the Columbia University slow neutron velocity spectrometer, Wu et al[6] measured the low energy total cross section of ^{59}Co in the following two energy ranges: 0.15 – 5.0 eV, and 0.5 – 5.0 eV. A fit of the total cross section of these two data runs gave essentially the same result:

$$\sigma_t(E) = 6.7 + 6.4 \ E^{-1/2} \quad barns$$

These results indicate significant inconsistencies in the scattering cross section of ^{59}Co, well outside the experimental errors.

The 2200 m/sec capture cross section of ^{59}Co have been measured by a variety of techniques. The second supplement to

the second edition of BNL 325[7] provides an adequate summary of the data prior to 1966. Since that time, new measurements have been carried out. These are indicated in Table 1.

Table 1

Recent Thermal Capture Measurements

Capture Cross Section (b)	Technique	Author
37.24 ± 0.11	pulsed neutron technique	Silk et al[8]
37.14 ± 0.24	activation	Merritt et al[9]
36.6 ± 0.5	activation	DeWorm[10]
37.75 ± 0.4	activation	Kim[11]

A total capture and a free-atom scattering cross sections of 37.2 ± 0.2b and 6.7 ± 0.3b are recommended in BNL 325, third edition[4]. After the completion of this evaluation a very recent measurement by Dilg et al[12] using slow neutrons energies between 0.0399 and 2.608 meV appeared in the literature. These authors determined σ_γ (2200 m/sec) = 37.15 ± .08b for ^{59}Co. Because of the widely discrepant scattering cross sections measured by Bernstein et al[5] and Wu et al[6] and mentioned previously (σ_s = 5 band 6.7b), Dilg crried out total cross section measurement at 1.25 eV. By subtracting the capture cross section at this energy from the total cross section, he derived a value of 6.3b for the scattering cross section of ^{59}Co. This is in good agreement, within the stated error, with the value recommended[4]

in BNL 325.

The coherent bound-atom scattering amplitude of ^{59}Co was determined by Roth[13] as 2.5 fm by the neutron diffraction technique. An additional measurement made by Moon[14] redetermined more accurately this quantity using the same technique. The result is:

$$b_{coh} = 2.50 \pm 0.03 \text{ fm}$$

A preliminary value reported by Koester and Knopf[15] and measured by small angle scattering is 2.35 ± .05 fm.

Polarization measurements at thermal and low neutron energies provides significant information about the spins of the 132 eV resonance and the bound level. Since the spin and parity of the ground state of ^{58}Co, I^{π} are $7/2^-$, s-wave neutron capture forms two possible compound states with spins of 4^- and 3^-. Transmission measurements with polarized monochromatic neutrons and polarized ^{59}Co nuclei by Schermer[16] showed that 78.3 ± 1.0 percent of the thermal capture is into J = 4 (I + 1/2) states. This value is based on a total capture cross section of 38.2b. In addition based on σ_s = 6.7b, (87 +1)% of the thermal scattering cross section is due to J = 3 (I - 1/2) states. The first resonance at 132 eV whose spins is established to be 4 (see Section III) contributes about 78.5% to the capture cross section. Since the contributions from spin 3 resonances is negligible, it follows that there is a negative energy resonance with spin 3 close

to neutron threshold.

In addition, by assuming a total free scattering cross section of 6.7b and a coherent scattering amplitude of 2.5 fm, Schermer[16] obtained two sets of solutions for b_+ and b_- with the aid of the following relations:

$$\sigma_s = 4\pi g_+ b_+^2 + 4\pi g_- b_-^2$$

$$b_{coh} = g_+ b_+ + g_- b_-$$

In these relations g_+ and g_- are the statistical weight factors and b_+ and b_- are the bound coherent scattering amplitudes due to $I + 1/2$ and $I - 1/2$ resonances respectively; σ_s is the bound scattering cross section and is related to the free scattering cross section by

$$\sigma_s \text{ (bound)} = \sigma_s \text{ (free)} \left(\frac{A+1}{A} \right)^2$$

The two solutions for b_+ and b_- are presented in Table 2.

Table II

	b_+ (fm)	b_- (fm)
Case 1	$+ 8.5 \pm 0.2$	$- 5.3 \pm 0.3$
Case 2	-3.5 ± 0.2	$+10.3 \pm 0.3$

Schermer[16] deduced that the second set satisfies his

polarization measurements at neutron energies of 0.0725 and 2.00 eV.

The polarized neutron diffraction technique was applied by Ito and Schull[17] to determine effectively the ratio b_i/b_{coh} where b_i is the incoherent scattering amplitude and is given by

$$b_i = \sqrt{g_+ \, g_-} \ (b_+ - b_-) = \frac{\sqrt{I(I+1)}}{2I+1} \ (b_+ - b_-)$$

By assuming $b_{coh} = 2.5$ fm, the coherent scattering amplitudes associated with the two possible spin states, 3 and 4, are calculated[17]. The results are as follows:

$b_+ = -3.80 \pm 0.54$ fm

$b_- = 10.60 \pm 0.70$ fm

These values are in agreement with the conclusions reached by Schermer[16] on the basis of polarized-beam transmission measurements.

The coherent scattering amplitudes associated with each spin state can be calculated from the resonance parameters with the aid of the relation:

$$b_\pm = 4\pi \left| R' + \sum_j \frac{\lambda_j \Gamma_{nj}}{2(E-E_j) + i\Gamma_j} \right|$$

where the summation is carried out over resonances with spins $j = I + 1/2$ and $I - 1/2$ separately.

III. Parameters of the 132 eV Resonance and the Absorption Reso-
nance Integral of ^{59}Co

The resonance parameters of the 132 eV resonance are par-
ticularly important because this resonance dominates thermal cap-
ture and gives the largest contribution to the absorption reso-
nance integral. In addition ^{59}Co is used as a flux monitor in
the energy region below 132 eV. In 1948, Seidl[18] studied the
132 eV resonance by the transmission method. Applying the Breit-
Wigner formula, he obtained two sets of solutions: $\Gamma = 2.0 \pm 0.1$
eV and $J = 4$ or $\Gamma = 5.0 \pm 0.5$ eV and $J = 3$. The measured peak
cross section of the resonance, $\sigma_o = 12{,}500 \pm 1250b$, favored a
spin assignment of 4 in accordance with the relation

$$\sigma_o = 4\pi \lambda^2 g \left(\frac{A+1}{A} \right)^2$$

Subsequently, Seidl et al[19] used the BNL fast chopper
facility to remeasure the resonance parameters of the 132 eV
resonance. Values of $\Gamma = 5.0 \pm .07$ eV and $\sigma_o = 9700 \pm 1800b$
were obtained.

More accurate and detailed determination of the parameters
of the resonance were carried out by Jain et al[20]. Based on a
comparison of the measured $2g\Gamma_n$ and Γ values, these authors de-
duced a spin assignment of 4 for this resonance. Measurement of
the γ ray intensity[20] determined the value of the radiative
width for the first time i.e. $\Gamma_\gamma = 0.40 \pm 0.04$ eV. Observa-

tions[21] of a reasonably strong γ ray transistion due to neutron capture in the 132 eV resonance and to the ground state of ^{60}Co with spin 5 confirmed a spin assignment of 4 for this resonance.

Measurement by Wall[22] of the difference in activation between a thick and thin disk-shaped detectors and its relation to the flux per unit lethargy at the lethargy of the main resonance of the detector showed that Γ_γ = 0.48 ± 0.04 eV for the 132 eV resonance. This value is somewhat larger than that obtained by Jain et al[20] and Moxon[23] but much smaller than the value reported by Block et al[24]. Very recently, by applying the technique of transmission measurements of several sample thicknesses, Bockoff et al[25] derived a radiative width which is in substantial agreement with the value deduced by Wall[22]. A summary of the up-to-date measurements of the resonance parameters of the 132 eV resonance is given in Table III. In this evaluation, the parameters of the 132 eV resonance recommended in BNL 325, third edition[4] were adopted.

As pointed out previously, since the major contribution to the absorpiton resonance integral, I_o, is due to the 132 eV resonance, an accurate knowledge of this quantity is important. Because of this fact, the experimental values of I_o measured since 1960 are compiled in Table IV. In this table are shown the reported values of the absorption resonance integrals I_o, the standard absorption resonance integral values used. For these cases, where the reduced absorption resonance integral, I_o', is reported, the 1/V contribution is added with the aid of the relation

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Table III

Resonance Parameters of the 132 eV Resonance

E_o	J	Γ (ev)	Γ_n (ev)	Γ_γ (ev)	Author
131.2			5.32±.05	0.46±.05	Bockhoff[25]
132			5.15±0.30		Garg[26]
132.0±0.5		6.0 ±0.2	5.15±.06		Nakajimo[27]
132.0±0.5	4	5.35±0.10	5.13±0.07	0.40±0.04	Jain[20]
130				0.44	Moxon[23]
132				0.67±0.15	Block[24]
134±2		5.2 ±0.7			Seidl[19]
132				0.48±.04	Wall[22]

Table IV

Absorption Resonance Integral

I_o (b)	Standard	Value (b)	Reference
77 ± 4	Au	I_o = 1550	Steinnes 72 [28]
72.6 ±4.0 [a]	B	σ = 760.8	Huttel 71 [29]
74.6 ± 3.0	Au	I_o = 1558	Schuman 69 [30]
75.7 ± 0.8	Au	I_o'= 1506	Kim 68 [31]
69			Wall 68
73.3 ± 2.0 [b]	Au	I_o = 1565	LeSage 66 [32]
68.6 ± 2.0 [c]	Au	I_o = 1565	LeSage 66 [32]
67.2 ± 4.0	Au	I_o = 1540	Carre 66 [33]
69.9 ± 3.5	Au	I_o = 1535	Eastwood 63 [34]
	Co	σ = 37.5	
72 ± 5			Dahlberg 61 [35]
∿70	Au	I_o'= 1513	Tattersall 60 [36]
75 ± 5	Au	I_o = 1565	Johnston 60 [37]
81 ± 4	Au	I_o = 1534	Feiner 60 [38]

(a) Value obtained by extrapolation to zero sample thickness.
(b) Value measured by Moxon-Rae detector.
(c) Values measured by the cadmium ratio method.

$$I \ (1/v) = 0.45 \ \sigma_\gamma \ (2200 \text{m/sec})$$

for a low energy cut off of 0.5 eV.

The values were normalized to a ^{197}Au absorption resonance integral of 1565 b. A weighted average value:

$$I_0 (^{59}\text{Co}) = 74.9 \pm 0.8 \ b$$

is obtained.

IV.   The Effective Nuclear Scattering Radius R'

Another parameter which is required in the calculation of
the total cross section is the effective nuclear scattering ra-
dius R' of ^{59}Co.   A survey of the literature indicated a wide
spread of values ranging from 5.3 to 6.8 fm.   This situation is
described in Table V.

Table V

Effective Nuclear Scattering Radius

R' (fm)	Method	Author	Ref
6.5	b	Pineo 70	39
5.3 ± 0.5	a	Nakajima 70	27
5.4 ± 0.5	a	Morgenstern 67	40
5.8 ± 0.5 (J=4)	a	Morgenstern 65	41
4.9 ± 0.5 (J=3)	a	Morgenstern 65	41
5.5 ± 0.6	b	Seth 64	42
6.8 ± 0.2	c	Andreef 63	43
6.2 ± 0.1	c	Ratinsky 60	44

Three methods were exploited in the extraction of the ef-
fective nuclear scattering radius:

(a)   In the region where resonances are well resolved, the
ability to shape fit the total or scattering cross section over
an extended energy range (particularly between resonances) en-
ables one to extract R'.

(b)   In the unresolved energy region, averaging the Breit-Wigner total cross section for s-wave resonances over an energy region containing many resonances, one obtains

$$<\sigma_T> = 4\pi (R')^2 + 2\pi^2 \lambda^2 \sqrt{E} \, S_o + 0 \, (S_o)^2$$

Usually, the contribution of higher order terms $0(S_o)^2$ in the keV energy range is small and can be neglected. By carrying out a least square fit to the average total cross section one can derive R' and S_o.

(c)   A variation on the above method is to measure the variation of average transmission $<T>$ at one neutron energy versus sample thickness. With the aid of the relation

$$<T> = \left(1 - \frac{\Gamma n}{D} \frac{A}{\Gamma}\right) e^{-n\sigma_p}$$

one obtains R' through the potential scattering cross section σ_p where

$$\sigma_p = 4\pi (R')^2$$

Shape analysis of the ^{59}Co transmission data below neutron energy of 77 keV by Morgenstern et al[40] gave $R' = 5.4 \pm 0.5$ fm. In an effort to search for a spin dependence of the scattering data, Morgenstern et al[40] fitted the transmission data in an

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energy region containing the resonances with spin 4 at 132 and 4320 eV. The result of this study gave R' = 5.8 ± 0.5 fm for J=4. To determine the scattering radius for J=3 the following conditions were imposed: (1) the coherent cross section = 0.78b, (2) the capture cross section due to the bound level with J=3 is 4.9b and (3) the total cross section passes through a minimum at 2350 eV. These restrictions gave R' = 4.9 ± 0.5 fm for J=3. The conclusion of this investigation is that there is *no convincing* evidence for a spin dependence of the scattering radius. Additional investigations by Morgenstern et al[41] yielded R' = 5.4 ± 0.5 fm. This is in agreement with a value of R' = 5.5 ± 0.6 fm determined by Seth et al[42] who applied the *average cross section* method. On the other hand, determination by Pineo[39], Andreef[43], and Ratinsky et al[44] gave results which are substantially larger than those of Morgenstern et al[40-41], Seth et al[42], and Nakajima et al[27].

In this evaluation, spin dependence of the scattering radius was not considered. As will be discussed subsequently, a fit of the total cross section data of Garg et al[45] supported the reported high values of R'.

V.   The Total Cross Section of ^{59}Co and the Evaluation Procedure

There are several measurements of the total cross section of ^{59}Co below 100 keV. Of these, two high resolution measurements reported in the literature are due to Garg et al[45] and Morgenstern et al[40-41] in the respective energy regions 0.14-128 keV and 1.38-500 keV. The total cross section measured by Garg et al[45] is available in the SCISRS Library. Unfortunately, the data of Morgenstern et al[40-41] is in transmission form, was not converted to total cross section by the authors, and is not available. In view of these considerations we applied the multilevel Breit-Wigner formalsim for a fitting of the data of Garg et al[45].

The technique of evaluating the total cross section from thermal energy to 100 keV proceeded along the following lines. As a starting point, the resonance parameters, the scattering radius, and the 2200 m/sec capture and scattering cross sections recommended[4] in BNL 325 were adopted. A multilevel Breit-Wigner total cross section curve was calculated using code RESEND[46]. The initial calculation showed that the fit to cross section between resonances is poor, thus indicating that the potential scattering cross section is not adequately described.

As a result, the following modifications were subsequently made:

(1)   The effective scattering radius R' was increased from 5.3 fm to 6.8 fm.

(2)   The change in R' necessitated a change in the bound state parameters. Those in BNL 325 (1973) are based on a scatter-

ing radius of 5.3 fm.

In order to fit the total cross section in the thermal energy range the following constrains were imposed $\sigma_\gamma = 37.2 \pm 0.2$b and $\sigma_s = 6.7 \pm 0.3$b.

It is important to note here that no attempt was made to fit the scattering and capture polarization data of Schermer[16] and Yto and Shull[17] since the available computer programs do not readily handle it. However, at the conclusion of the evaluation an effort was made to divide the resonances according to their spins, create two files, and then calculate the capture and scattering cross sections with the aid of INTER code[47]. The results will be discussed in a subsequent section.

Additional changes are the following:

(3) Unknown J values were assigned the values J=3 or J=4 at random with an attempt being made to keep the level density proportional to 2J+1 and considering the level repulsion law.

(4) A few small resonances, possibly p-wave, were eliminated and some in the high energy region were shifted slightly.

(5) Unknown radiative widths above E_n = 18.92 keV were assigned the value Γ_γ = 0.48 eV up to 90.0 keV. However above 90 keV, Γ_γ was set equal to 1.5 eV in order to improve the fit with the capture data above 100 keV. The capture data of Spencer and Beer[48] from which radiative widths were extracted in the energy range 8.05-56.4 keV were not yet available.

Table VI shows the resonance parameters used in the present evaluation. With these resonance parameters the fit to Garg et

Table VI

Resonance Parameters of ^{59}Co

E_o (kev)	J	Γ (eV)	Γ_n (eV)	Γ_γ (eV)
-0.521	3	50.15	49.67	0.48
0.132	4	5.60	5.12	0.48
1.380	3	0.4856	.0056	0.48
2.850	4	0.585	0.105	0.48
3.980	3	0.570	0.09	0.48
4.322	4	110.48	110.00	0.48
5.015	3	652.00	651.00	1.00
6.380	4	2.22	2.00	0.22
8.050	3	37.30	37.00	0.30
8.750	4	1.14	0.82	0.32
9.690	3	3.26	2.70	0.56
10.700	4	65.53	64.90	0.63
11.850	3	2.75	2.50	0.25
13.280	4	21.65	21.00	0.65
15.640	3	74.57	74.10	0.47
16.920	4	165.52	165.00	0.52
19.750	4	3.28	2.80	0.48
21.940	3	745.48	745.00	0.48
22.510	4	253.48	253.00	0.48
24.460	3	360.48	360.00	0.48
25.150	4	184.48	184.00	0.48
25.920	4	25.48	25.00	0.48

Table VI (Cont.)

E_o (keV)	J	Γ (eV)	Γ_n (eV)	Γ_γ (eV)
27.350	4	170.48	170.00	0.48
29.400	3	16.48	16.00	0.48
30.110	4	327.48	327.00	0.48
31.360	3	155.48	155.00	0.48
31.760	4	8.88	8.40	0.48
32.730	3	142.48	142.00	0.48
33.050	4	44.48	44.00	0.48
34.510	3	6.18	5.70	0.48
34.900	4	246.48	246.00	0.48
36.740	3	26.48	26.00	0.48
40.250	3	27.48	27.00	0.48
40.670	4	3.68	3.20	0.48
41.480	4	36.48	36.00	0.48
42.81	4	3.18	2.70	0.48
43.610	3	3.88	3.40	0.48
45.230	3	323.48	323.00	0.48
45.970	4	300.48	300.00	0.48
47.140	4	40.48	40.00	0.48
51.260	4	480.48	480.00	0.48
52.850	4	52.38	51.90	0.48
53.830	3	500.48	500.00	0.48
56.450	3	200.48	200.00	0.48
57.740	4	18.48	18.00	0.48
58.940	3	341.48	341.00	0.48

Table VI (Cont.)

E_o (keV)	J	Γ (eV)	Γ_n (eV)	Γ_γ (eV)
59.760	4	100.08	99.60	0.48
61.080	3	91.48	91.00	0.48
62.800	4	39.48	39.00	0.48
66.040	3	87.48	87.00	0.48
69.510	4	20.48	20.00	0.48
69.960	4	210.48	210.00	0.48
71.870	3	416.48	416.00	0.48
72.310	3	219.48	219.00	0.48
74.470	4	4.48	4.00	0.48
74.730	4	36.48	36.00	0.48
75.700	3	11.48	11.00	0.48
75.890	4	9.48	9.00	0.48
76.530	3	21.48	21.00	0.48
77.000	3	400.48	400.00	0.48
77.720	4	9.48	9.00	0.48
78.780	3	11.48	11.00	0.48
79.450	4	249.48	249.00	0.48
81.650	3	229.48	229.00	0.48
83.140	3	219.48	219.00	0.48
84.200	4	212.48	212.00	0.48
86.290	3	23.48	23.00	0.48
88.800	4	1156.48	1156.00	0.48
89.050	4	27.48	27.00	0.48
91.510	3	36.50	35.00	1.50

Table VI (Cont.)

E_O (keV)	J	Γ (eV)	Γ_n (eV)	Γ_γ (eV)
92.700	4	339.50	338.00	1.50
92.780	3	2698.5	2697.0	1.50
94.800	4	428.50	427.0	1.50
95.110	3	86.50	85.0	1.50
97.630	3	595.50	594.00	1.50
98.300	4	2988.5	2987.00	1.50
100.280	3	131.50	130.00	1.50
101.640	3	344.50	343.00	1.50
105.330	3	252.50	251.00	1.50
106.630	4	230.50	229.00	1.50
108.830	3	252.50	251.00	1.50
110.050	4	143.50	142.00	1.50
110.950	3	92.50	91.00	1.50
111.400	4	19.50	18.00	1.50
112.120	3	143.50	142.00	1.50
113.210	4	134.50	133.00	1.50
114.110	3	19.50	18.00	1.50
114.870	3	1212.50	1211.00	1.50
116.440	4	90.50	89.00	1.50
117.260	4	605.50	604.00	1.50
118.630	3	1395.50	1394.00	1.50
119.400	4	410.40	408.90	1.50

al's [45] data was generally good. However, for further improve-
ments, a small background contribution no large than ± lb in
energy regions 1-95 keV to the elastic scattering cross was in-
troduced in File 3 in small, selected energy regions. The solid
curve in Figure 1, which is a doppler broadened RESEND [46] calcu-
lation, shows the evaluated total cross section in the energy
range from 0.01 to 10.0 eV. As shown, it passes close to the data
points of Bernstein et al [5] at the low energy end and in the en-
ergy region 0.1-1.0 eV there are significant deviations from the
data points of Bernstein et al [5]. However, at higher energies
1-10 eV the calculated cross section well describes the data
points of Wu et al [6].

Figure 2 describes the doppler broadened cross section in
the energy range 10-1000 eV, comprising the important 132 eV
resonance, and compares it with the measurements of Cote et al [49],
Wu et al [6], Seidl et al [19], and Merrison et al [50].

Figures 3-7 show the evaluated total cross section in the
respective following regions 1.0-10.0 keV, 10.0-25.0 keV, 25.0-
50.0 keV, 50.0-75.0 keV, and 75.0-100.0 keV. As shown, the fit to
the data of Garg et al [45] is generally good except for the thin
sharp resonances. This is mainly due to the fact that resolution
broadening was not applied in these calculations. Subseqent
calculations taking into account resolution broadening indicated
substantial improvement in the fit to the thin sharp resonances,
examples of which are at energies of 6.38, 8.75, 9.69, 11.85,
19.75, 25.92, 29.4 keV in Figures 8, 9, 10. At the completion of

the present evaluation, the resonance parameters of Garg and

Rainwater[51] were communicated to us.   In general there is rea-

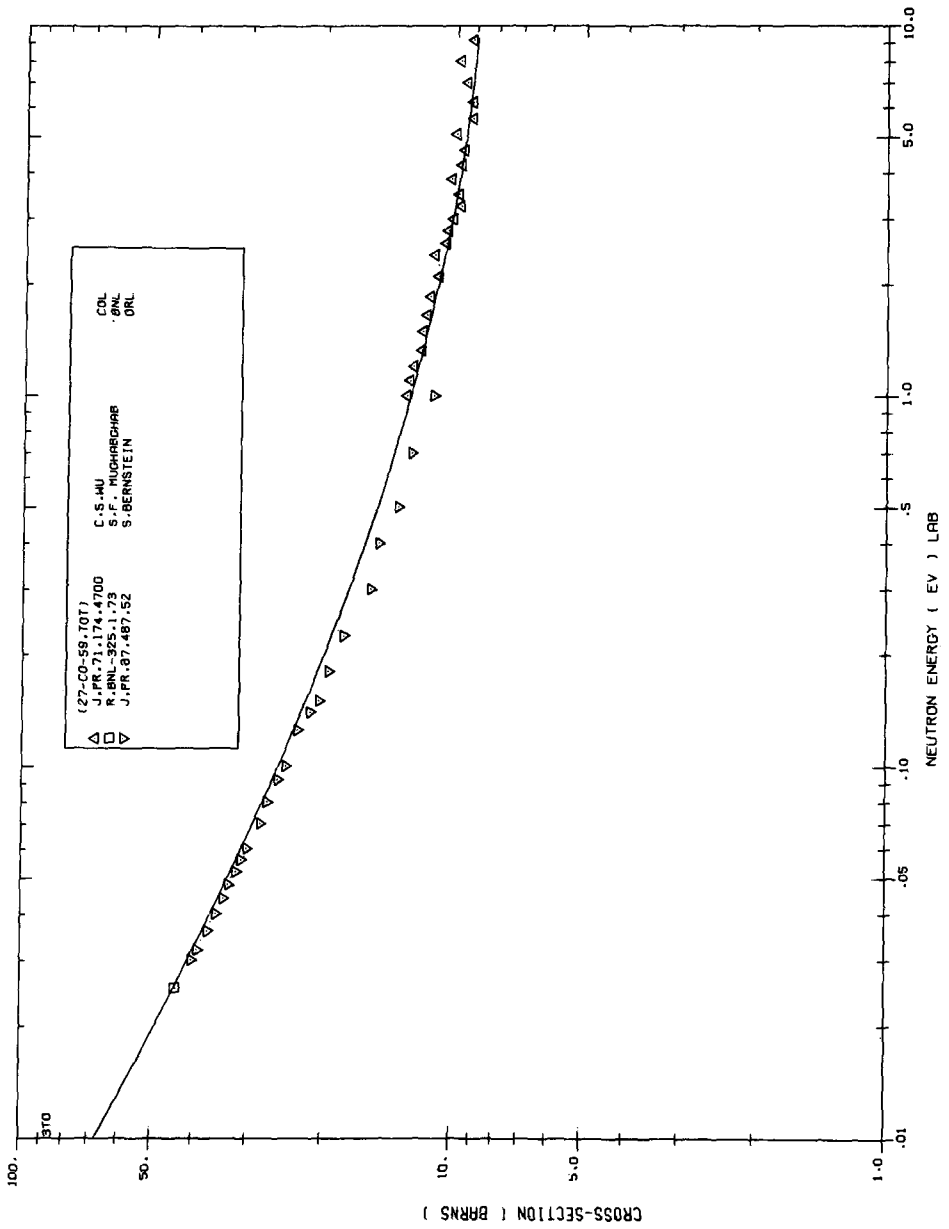sonably good agreement between the two resonance-parameter-data

sets.

Figure 1.

CROSS-SECTION (BARNS)

NEUTRON ENERGY (EV) LAB

(27-CO-59.TOT)
J.PR.71.174.4700   C.S.WU   COL
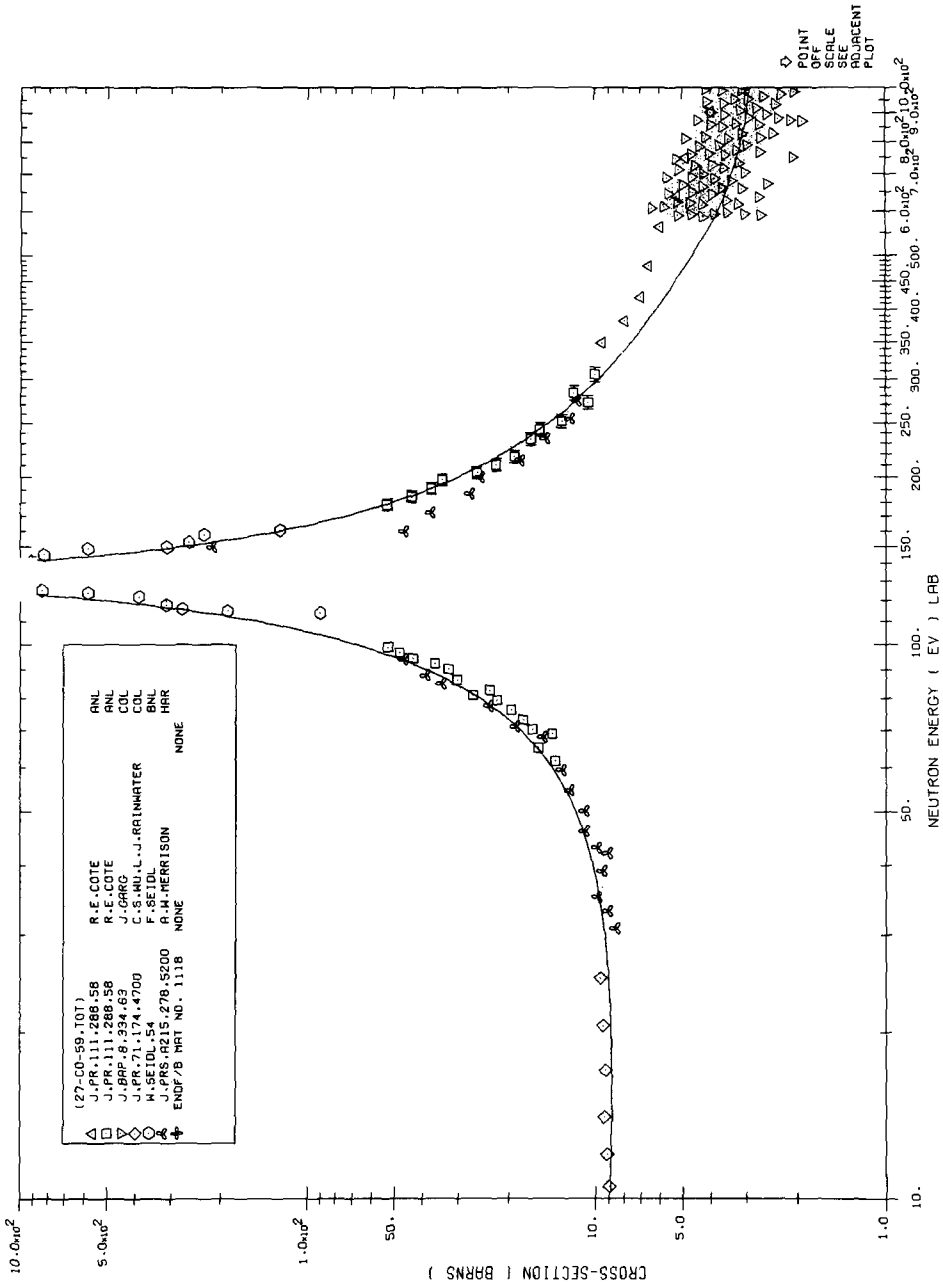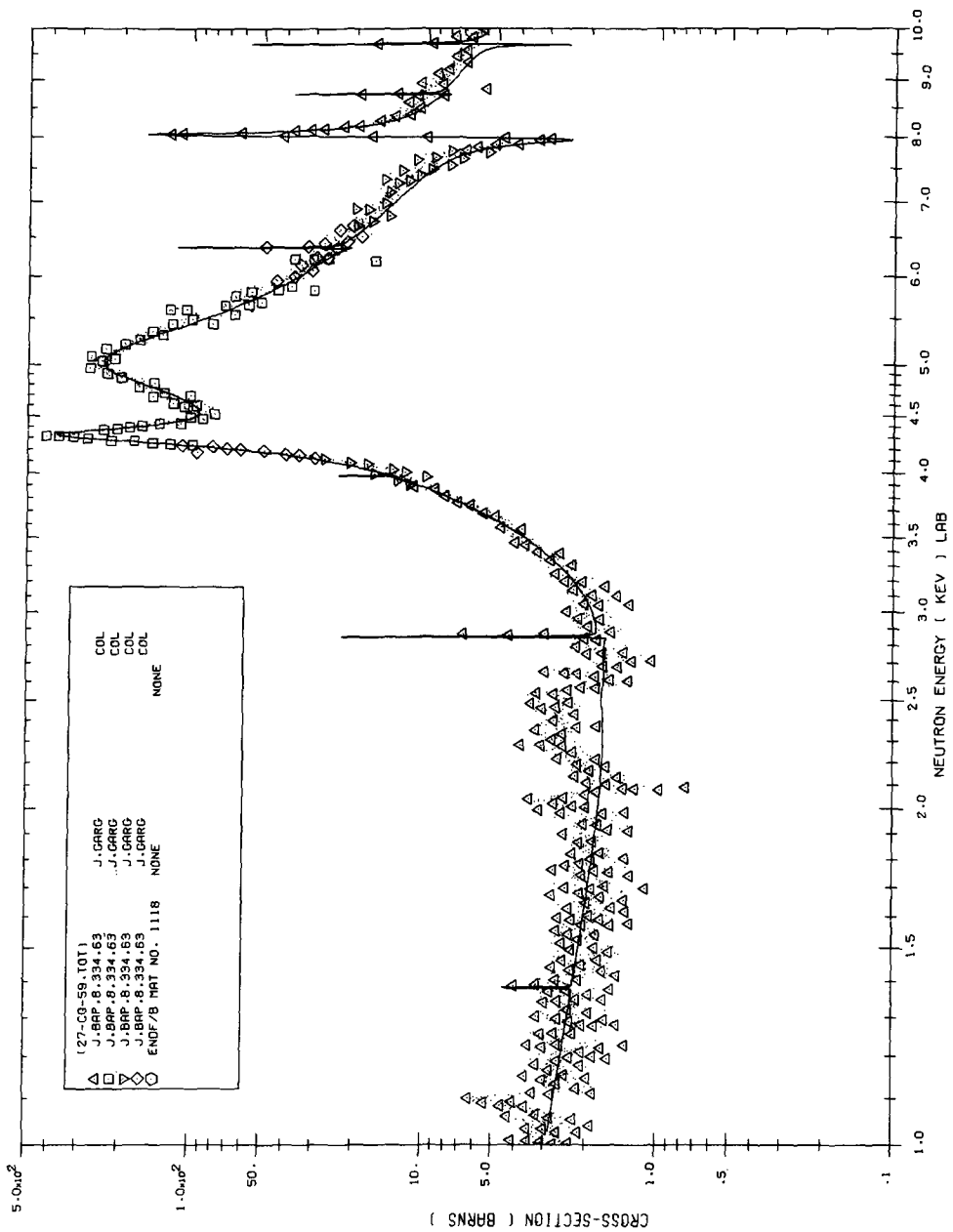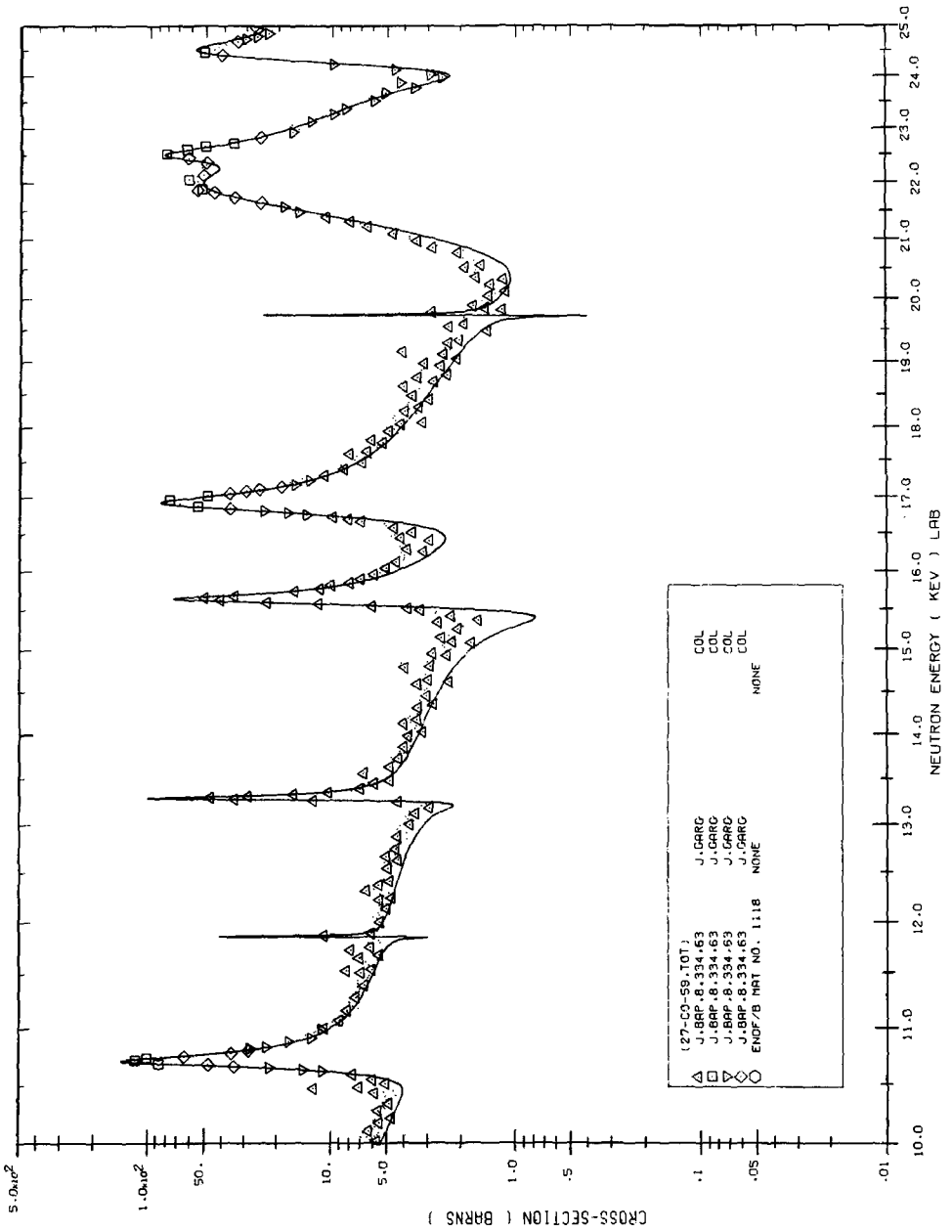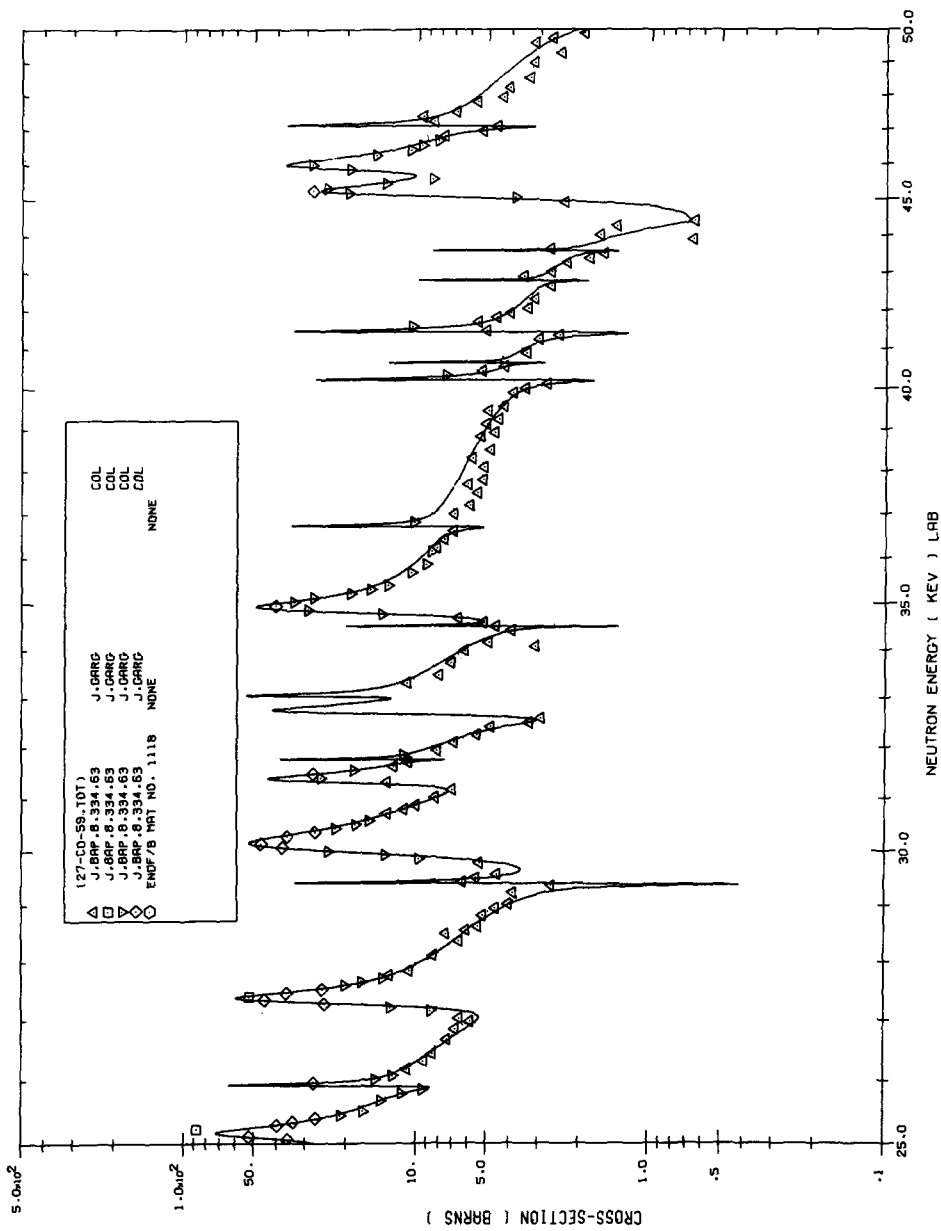R.BNL-325.1.73   S.F.MUGHABGHAB   BNL
J.PR.87.487.52   S.BERNSTEIN   ORL

Figure 2.

Figure 3.

Figure 4.

Figure 5.
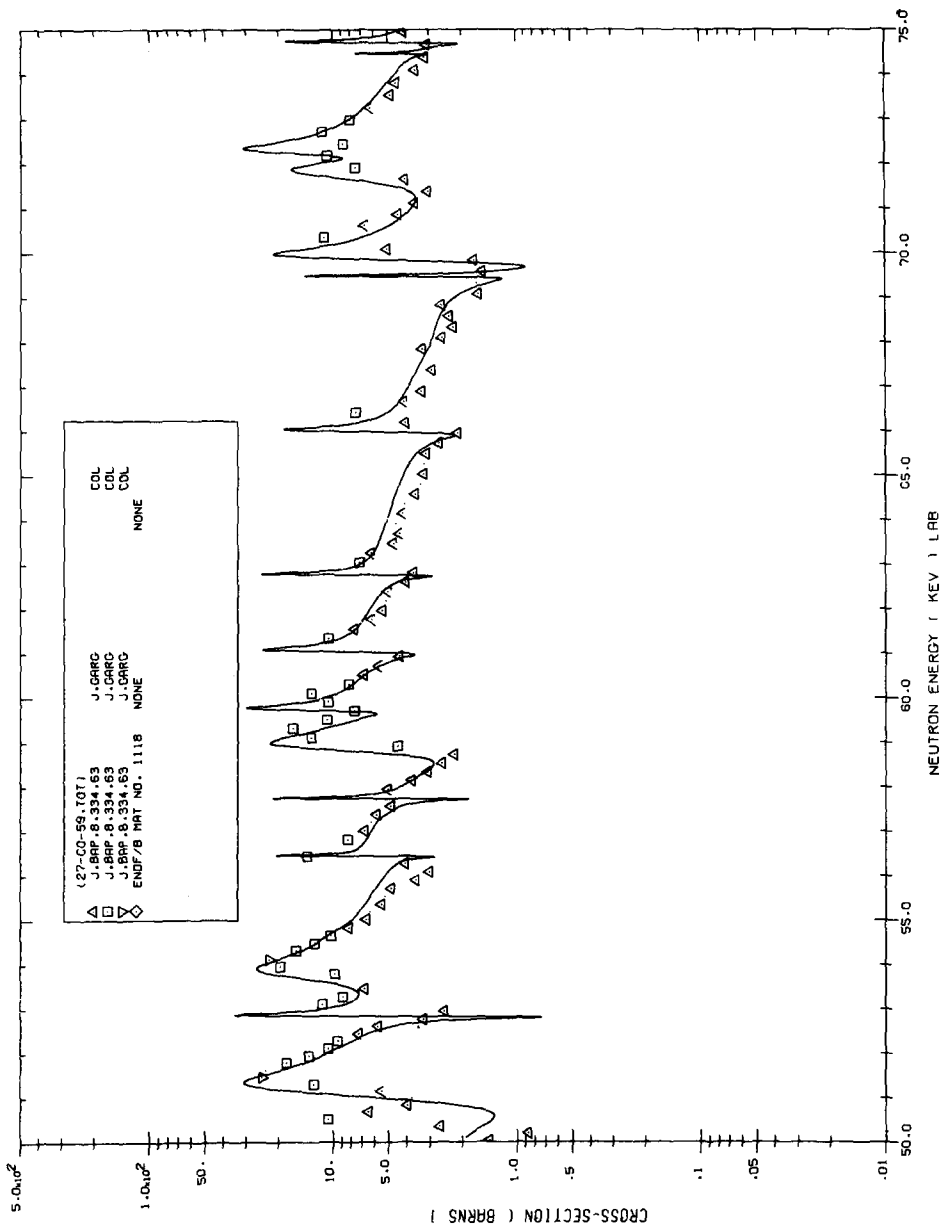
Figure 6.
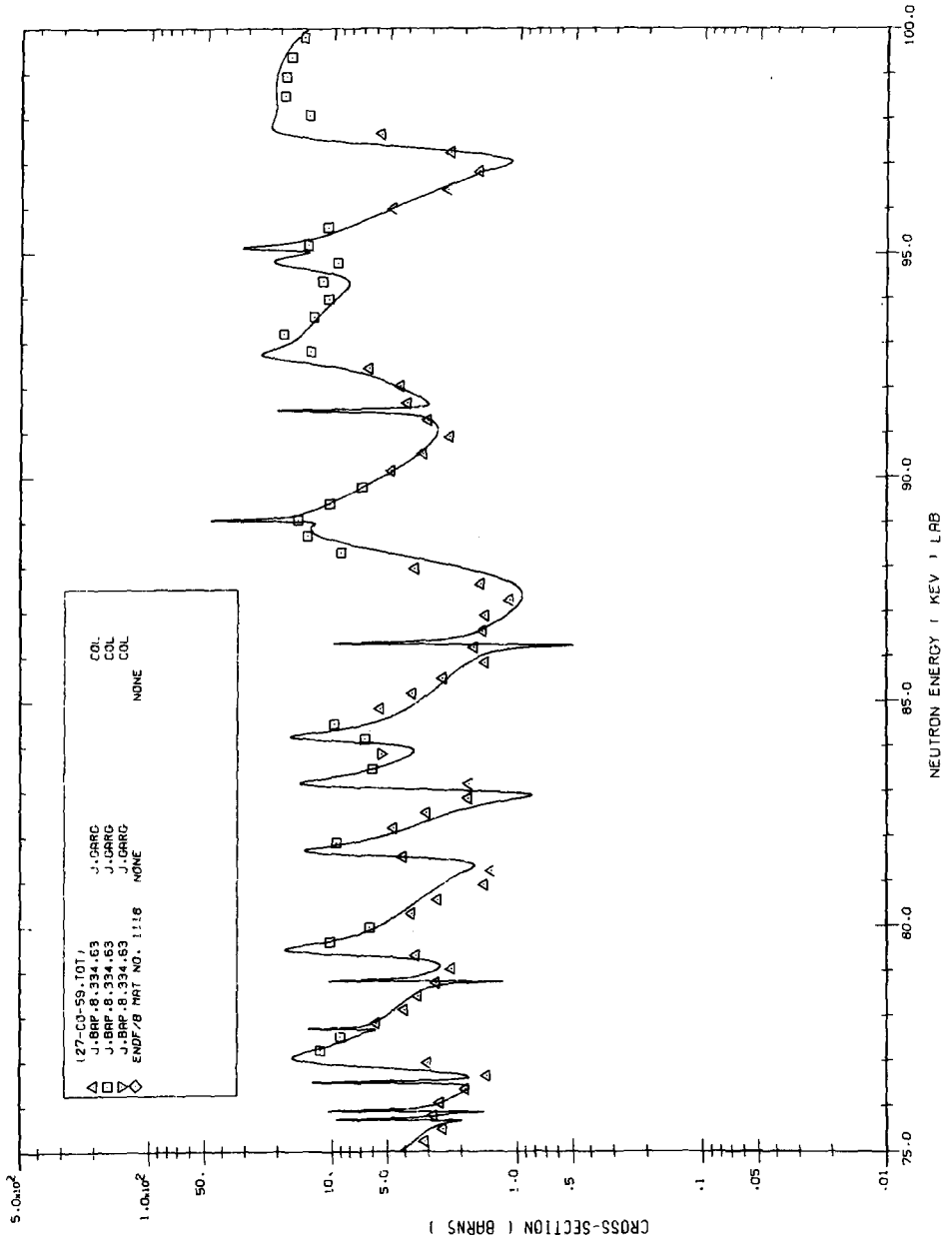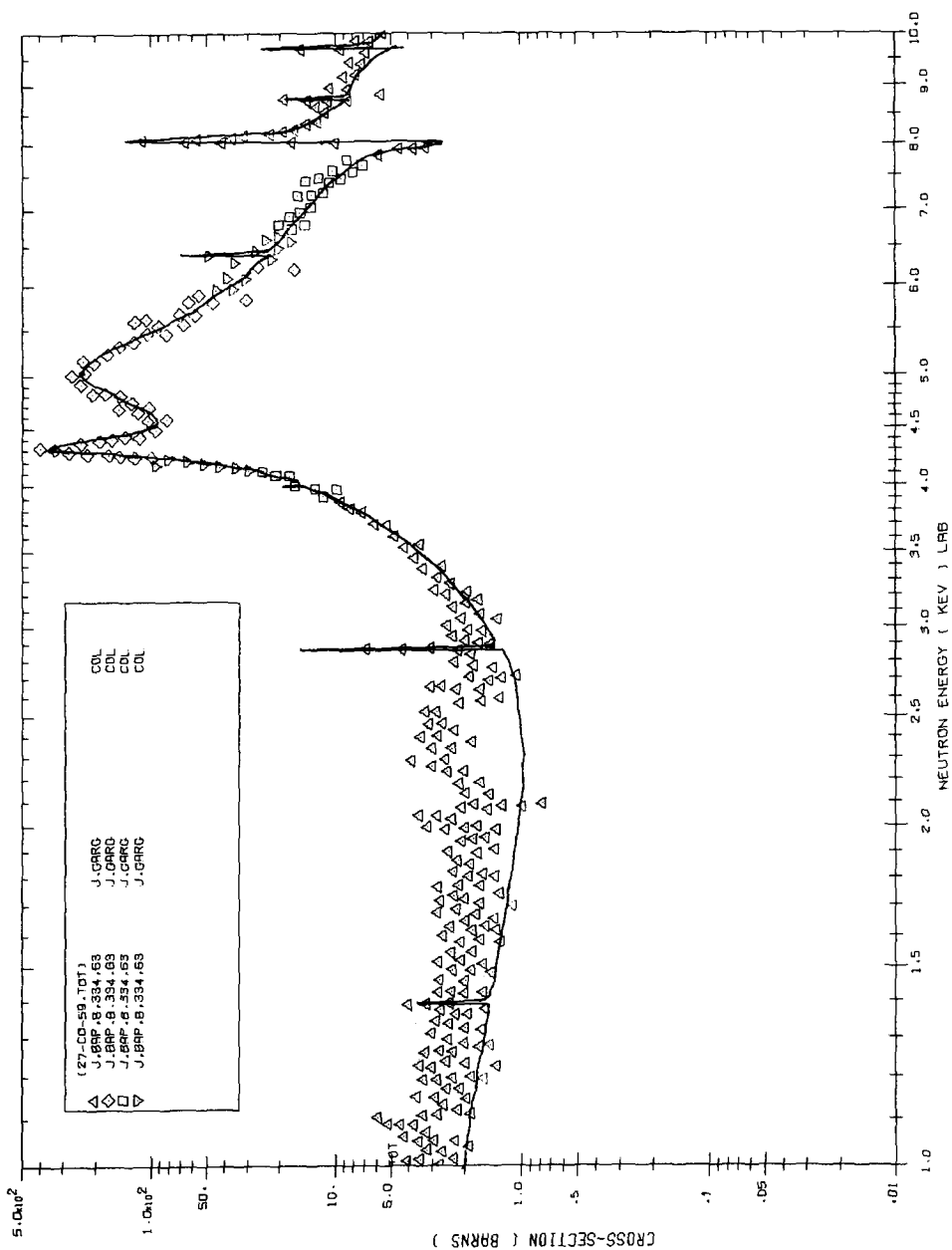
Figure 7.

CROSS-SECTION (BARNS)

NEUTRON ENERGY (KEV) LAB

(27-CO-59.TOT)
J.BRP.8.334.63   J.GARG   COL
J.BRP.8.334.63   J.GARG   COL
J.BRP.8.334.63   J.GARG   COL
ENDF/B MAT NO. 1118   NONE   NONE

- 30 -

Figure 8.

Figure 9.

Figure 10.

NEUTRON ENERGY (KEV) LAB

CROSS-SECTION (BARNS)
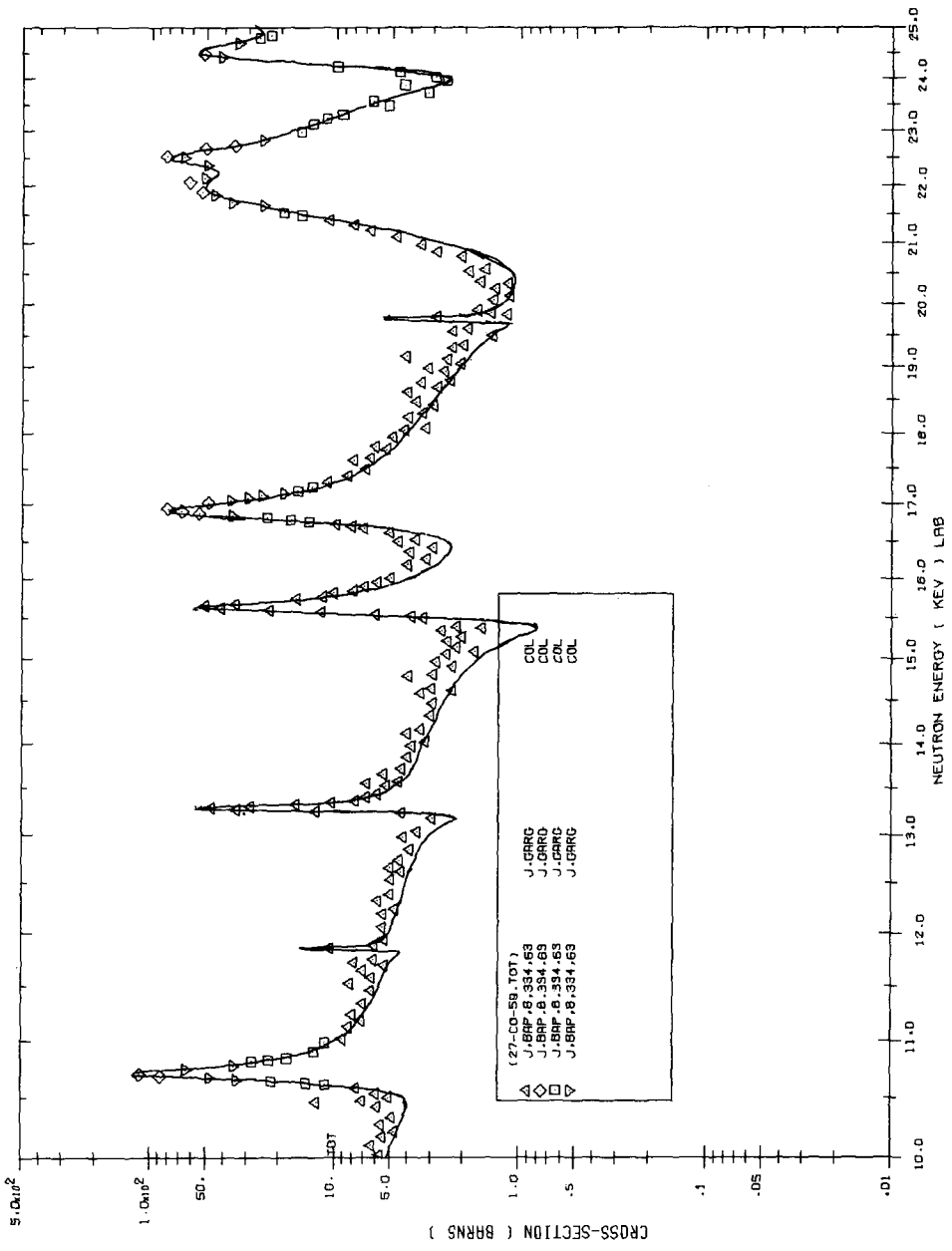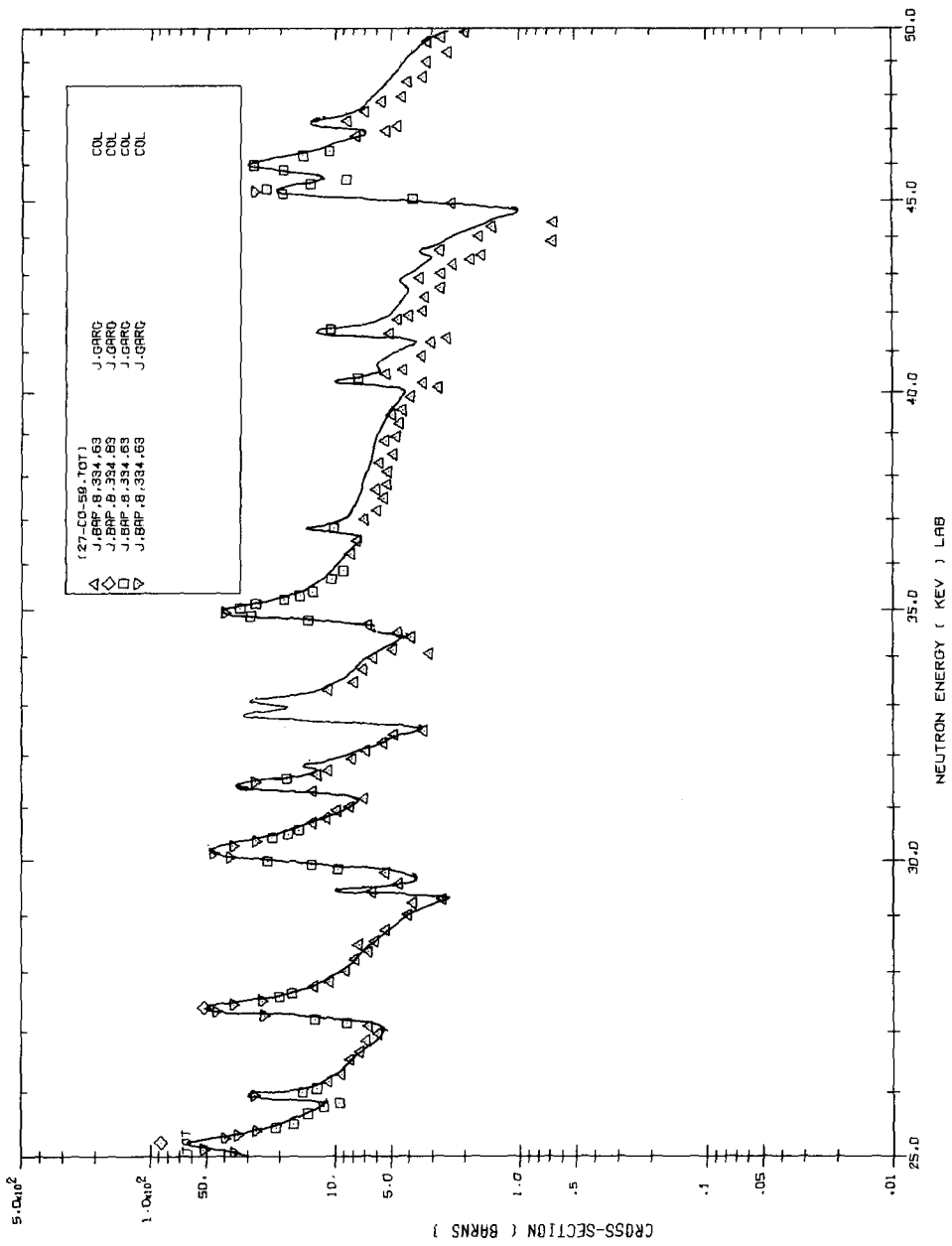
IV.   Comparison with Polarization Data

As pointed out previously, at the completion of the evaluation, two data files for each spin state were prepared. Calculations of capture and scattering cross sections were carried out with the aid of the code INTER[47]. The scattering cross sections at thermal energies due to spin 3 and 4 resonances are found to be 12.94b and 1.71b respectively. From these values, one calculates bound coherent scattering amplitudes of 10.32 fm and −3.75 fm for J=3 and J=4 resonances. These values are in excellent agreement with the measurements of Ito and Shull[17]. The results of the scattering data are summarized in Table VII.

Table VII

Scattering Cross Sections Due to

Two Spin States 3 and 4

	J=3	J=4
Free σ_{sc} (b)	12.94	1.71
Free a_{coh} (fm)	10.15	−3.69
Bound b_{coh} (fm)	10.32	−3.75
Exp. b_{coh} (fm)	10.60 ± 0.70	−3.80 ± 0.54

In addition, the capture and scattering cross sections at the following energies, 0.0253, 0.0725, and 2.11 eV for both spin states were determined. The results are presented in Table VIII.

Table VIII

Thermal Cross Sections for the Two Spin States

at En = 0.0253, 0.0725, and 2.11 eV

E_n (eV)	0.0253		0.0725		2.11	
Spin State	J=3	J=4	J=3	J=4	J=3	J=4
Capture (b)	7.83	29.39	4.55	17.37	0.85	3.32
Scattering (b)	12.94	1.71	12.94	1.71	12.85	1.83
Total (b)	13.77	31.10	17.49	10.08	13.70	5.15

From the values presented in Table VIII, one calculates that at E_n = 0.0725 eV, 79.2% of the capture is into the J=4 states and that 85.1% of the scattering is into J=3 states. These numbers are in very good agreement with the experimental numbers within the stated errors reported by Schermer[16] and presented also in Table IX.

Table IX

Comparison of the Calculation with

the Experimental Polarization Data

Capture at 0.0725 eV	Into J=4 States
Experimental	78.7 ± 1.0%*
Present Evaluation	79.2%
Capture at 2.11 eV	
Experimental	85.5 ± 5.4%*
Present Evaluation	79.6%
Scattering at 0.0725	By J=3 Resonance
Experimental	87 ± 1%
Present Evaluation	85.1%

*Value renormalized to σ_γ (2200 m/sec) = 37.2b

V.   Summary, Conclusion, and Epilogue

An evaluation of the ^{59}Co neutron cross sections in the en-
ergy range 10^{-5}eV-100 keV for ENDF/BIV has been performed. The
total and scattering cross sections are described by a multilevel
Breit-Wigner resonance parameters. The capture cross section is
calculated by single level Breit-Wigner formalism. The parameters
of a bound level with spin 3 for a description of the thermal en-
ergy region are derived. It was not necessary to invoke an addi-
tional bound level with spin 4 as was done in a previous evalu-
ation[52]. As pointed out in the introduction, this difference is
due to the fact that a radiative width of 0.48 eV is used in the
present evaluation for the 132 eV resonance (J=4) instead of
0.40 eV as was assumed in the previous one[52]. A radiative width
of 0.48 eV gives better agreement with the *absorption resonance*
integral. The parameters of a bound level with J=4 as reported
by Abrahms et al[53] should be disregarded since the derivation is
based on an incorrect assumption of adding γ ray intensities in-
coherently i.e. *neglecting interference terms*. The nuclear
scattering radius was determined to be 6.8 fm. This is in good
agreement with the optical model calculations[54] (R'=6.6 fm) and
the results of Pineo[39], Ratinsky et al[44] and Andreef[43] but
not with the results of Morgenstern et al[40-41] and Nakajima et
al[27].

The resonance capture integral (lower limit of 0.5 eV) calcu-
lated from the present resonance parameters and including contri-
bution above 100 keV is 76.7b. This is in reasonable agreement

with a weighted average experimental value of 74.9 ± 0.8b and
with a value of 75.5 ± 1.5 b recommended[4] in BNL 325 (1973).
The Wescott g factor for capture calculated here is determined as
0.99996. The thermal cross sections are as follows:

Thermal Capture Cross Section	=	37.22 b
Thermal Elastic Scattering Cross Section	=	6.62 b
Thermal Total Cross Section	=	43.84 b

After the completion of this evaluation Koester et al[55]
reported measurements of the total free-atom scattering cross sec-
tion σ_{sc} and the coherent scattering amplitude. The values are:

$$\sigma_{sc} = 5.95 \pm 0.65 \text{ b}$$
$$b_c = 2.78 \pm 0.04 \text{ fm}$$

From these quantities, the scattering amplitudes b_+ and b_- corre-
sponding to spin $I + 1/2$ and $I - 1/2$ states are calculated[55].
The results are:

$$b_+ = -2.78 \pm 0.04 \text{ fm}$$
$$b_- = +9.91 \pm 0.06 \text{ fm}$$

These quantities are in strong disagreement with the values
reported by Ito and Shull[16]. In addition, these results imply
that 91 ± 1% of the scattering is due to $(I-1/2)$ spin states in

wide contrast to the 87 ± 1% value reported by Schermer[16].

Furthermore, there are large differences outside the stated errors, between the scattering cross section and the coherent scattering amplitude reported by Koester et al[55] and those of Moon[16], Roth[13], and Wu et al[6]. It is difficult to accept that all of the previous measurements are erroneous. In the present evaluation, a reliance on a scattering cross section of 6.7 b was made in order to derive the parameters of a bound level with spin 3. Note that (1) a nuclear scattering radius of 6.8 fm was derived from the high energy region and (2) since bound states with spin 4 are not invoked, it follows that the value b_+ is independent of the free atom scattering cross section, i.e. it depends on R' and the positive energy resonances. In the present evaluation we find

$$b_+ = -3.75 \text{ fm}$$

which is in good agreement with the value reported by Ito and Shull[17] but not that of Koester et al[54]. Very recent measurement of the total cross section of ^{59}Co at 18.8 eV were completed[56]. From these measurements, Dilg[56] derived a thermal scattering cross section of 6.11 ± 0.10 b which is in agreement with the recent results of Koester et al but not Salama et al[57]. $(\sigma_s = 7.20 \pm 0.06b)$ These new results should be considered in a future evaluation of the thermal scattering cross section of ^{59}Co.

ACKNOWLEDGMENTS

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