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Institut für Angewandte Kernphysik
Projekt Schneller Brüter

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ABSTRACT

Neutron total cross sections of ^{63}Cu and ^{65}Cu have been determined in the energy region from 34 - 150 keV by means of transmission measurements on enriched samples. R-matrix fits to the transmission data were carried out and the parameters which were derived are presented.

DER TOTALE NEUTRONENWIRKUNGSQUERSCHNITT
VON ^{63}Cu UND ^{65}Cu IM ENERGIEBEREICH 34 - 150 keV

ZUSAMMENFASSUNG

Die totalen Wirkungsquerschnitte von ^{63}Cu und ^{65}Cu wurden im Energiebereich von 34-150 keV durch Transmissionsmessungen angereicherter Proben bestimmt. R-Matrix-Fits an die Transmissionsdaten wurden durchgeführt und die abgeleiteten Parameter werden vorgelegt.

INTRODUCTION

The resonance parameters of ^{63}Cu and ^{65}Cu up to about 30 keV neutron energy are well established by measurements of several authors (1), (2), (3). At higher energies from 34 keV to 150 keV transmission measurements have been carried out by Müller and Rohr (4), with the pulsed 3 MV Karlsruhe Van de Graaff. In order to complete this work an R-matrix multilevel fit to the transmission data by means of the FORTRAN IV code FANAL II (5) was performed. The resonance parameters were used to establish neutron width and spacing distributions and to calculate s-wave neutron strength functions.

EXPERIMENTAL METHOD

The technique of time-of-flight transmission measurements was the same as described in earlier publications (6). Neutrons were produced in a thick Lithium target via the ^{7}Li (p,n) ^{7}Be reaction with a pulsed 1 ns wide proton beam at the 3 MV Karlsruhe Van de Graaff. At a flight path of 10.36 m a proton recoil detector was used as a neutron counter. The time resolution achieved was about 0.6 ns/m. The energy range of 34-150 keV was covered in two runs, one from 34 - 80 keV and the second from 80 - 150 keV. Table I lists the quantities of the sample materials used and the corresponding isotopic abundances.

RESULTS AND DISCUSSION

The transmission values computed from the corresponding time-of-flight spectra with and without sample were shape fitted with the FORTRAN IV code FANAL II (5). The program uses an R-matrix multilevel formalism, as described by Lane and Thomas (7) and calculates chi-square fits of the transmission data including a correction for the contaminants and the oxygen content. For the computation of the oxygen cross section a potential scattering radius of 5.6 fm was used. The program delivers the resonance parameters, the potential scattering radius and for each spin state a strength function like variable S'_J which takes into account the resonances outside the analysed region. The resolution broadening of the resonances was taken as a Gaussian. A correction for the Doppler broadening which in general is negligible for the broad s-wave resonances was not performed.

Figures 1 - 4 show the shape fitted transmission data and the total cross section derived from the resonance parameters. Fig. 10 gives the unresolved total cross section data of ^{65}Cu in the energy region 150-260 keV.

In the 34 keV to 60 keV energy region resonance parameters have also been reported by Good et al. (1). The differences between our results and those of ref. (1) are attributed to our better energy resolution. The ^{63}Cu resonances at 36.4 keV and 42.2 keV of ref. (1) were found to be doublets in the present measurement, and instead of the ^{65}Cu resonance at 43.5 keV of ref. (1) three closely spaced resonances were observed.

The 2 g Γ_n values of the ^{65}Cu resonances at 54.2 keV and 58 keV of ref. (1) are larger than the present results, probably due to the inclusion of smaller nearby resonances which we have analysed. From the shape analysis a spin two assignment for the ^{65}Cu resonance at 34.84 keV is more likely than the spin one which may be deduced from the 2 g Γ_n value of ref. (1). The 2 g Γ_n values of the ^{65}Cu resonances at 50.8 keV and 39.7 keV of ref. (1) are in fair agreement with the present results.

The relatively large number of analysed resonance parameters were used to establish width and spacing distributions and to calculate strength functions. The experimentally observed width distributions give an idea of the missed small levels . In all cases about 10 levels were not resolved or incorrectly assigned as $\ell > 0$ wave resonances. The spacing distribution was compared with the Wigner distribution. The 102 levels of the two spin states together should be correctly described by a Wigner distribution of two populations (8). The experimentally observed distribution does not seem to fit this concept very well (Fig. 9). However the inclusion of the missed levels which introduces more smaller spacings would probably improve the fit to the Wigner distribution of two populations. Table IV lists the strength functions calculated independently of spin and for each spin state. The values are in agreement with values given by Good et al. (1) and Julien et al. (2) within the quoted uncertainties. Julien (9) has reported a J dependence of the strength functions for nuclei with spin 3/2, i.e. in particular for the copper isotopes. However, our more accurate copper strength functions do not confirm this result.

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Table I Sample characteristics

Sample material	Isotopic composition (atomic percent) ^{63}Cu	^{65}Cu
0.0564 atm/b (4.18 g CuO)	99.62	0.38
0.0498 atm/b (3.78 g CuO)	3.04	96.96

Table II

The resonance parameters of ^{63}Cu

E_o (keV)	Γ_n (keV)	$g\Gamma_n$ (keV)	ℓ	J
36.13 ± 0.11	0.12 ± 0.01		0	1
36.83 ± 0.11	0.06 ± 0.01		0	2
37.95 ± 0.12		≃0.007	> 0	
39.38 ± 0.13	≃0.008		0	2
40.22 ± 0.13	≃0.008		0	2
40.60 ± 0.13	0.02 ± 0.01		0	1
41.98 ± 0.14	0.15 ± 0.01		0	2
42.49 ± 0.14	0.28 ± 0.01		0	1
44.07 ± 0.15		≃0.004	> 0	
44.75 ± 0.15	0.05 ± 0.01		0	1
47.48 ± 0.17		≃0.008	> 0	
47.72 ± 0.17	0.02 ± 0.01		0	2
48.23 ± 0.17	≃0.004		0	1
50.25 ± 0.18	0.10 ± 0.01		0	1
53.1 ± 0.2	0.04 ± 0.01		0	2
53.7 ± 0.2	0.65 ± 0.02		0	1
54.9 ± 0.2	0.28 ± 0.01		0	2
55.3 ± 0.2	0.61 ± 0.02		0	1
56.3 ± 0.2	0.08 ± 0.01		0	2
57.6 ± 0.2	≃0.006		0	2
58.4 ± 0.2	0.05 ± 0.01		0	2
59.1 ± 0.2	0.02 ± 0.01		0	2
59.6 ± 0.2		≃0.006	> 0	
59.8 ± 0.2		≃0.009	> 0	
60.2 ± 0.2	0.02 ± 0.01		0	1
63.19 ± 0.25	0.05 ± 0.01		0	2
65.0 ± 0.3	0.26 ± 0.02		0	1
66.3 ± 0.3	0.28 ± 0.02		0	1
69.6 ± 0.3	0.14 ± 0.01		0	1
71.2 ± 0.3	0.02 ± 0.01		0	2
72.2 ± 0.3		0.04 ± 0.01	> 0	
72.7 ± 0.3	0.42 ± 0.02		0	2
73.3 ± 0.3		0.02 ± 0.01	> 0	
73.6 ± 0.3	0.54 ± 0.02		0	1
74.5 ± 0.3	0.05 ± 0.01		0	1
75.9 ± 0.3	0.03 ± 0.01		0	2
77.7 ± 0.4	0.04 ± 0.01		0	1
79.0 ± 0.4	0.06 ± 0.01		0	2
81.4 ± 0.4	0.74 ± 0.03		0	2
87.5 ± 0.4		≃0.01	> 0	
89.7 ± 0.4	0.40 ± 0.02		0	1
91.3 ± 0.4	0.15 ± 0.02		0	2
92.1 ± 0.4	0.07 ± 0.01		0	2

Table II

The resonance parameters of ^{63}Cu (continued)

E_o (keV)	Γ_n (keV)	$g\Gamma_n$ (keV)	ℓ	J
94.6 ± 0.4	0.14 ± 0.02		0	1
95.5 ± 0.4		0.03 ± 0.01	>0	
95.9 ± 0.4	0.14 ± 0.02		0	2
96.9 ± 0.4		≃0.016	>0	
100.2 ± 0.4		≃0.016	>0	
100.8 ± 0.5	0.37 ± 0.02		0	1
101.3 ± 0.5	0.15 ± 0.02		0	2
103.7 ± 0.5	0.14 ± 0.02		0	2
105.2 ± 0.5		0.04 ± 0.01	>0	
107.4 ± 0.5	0.42 ± 0.03		0	2
108.7 ± 0.5	0.23 ± 0.02		0	2
114.7 ± 0.6	0.08 ± 0.01		0	2
118.2 ± 0.6	0.22 ± 0.03		0	1
119.5 ± 0.6	0.15 ± 0.02		0	1
123.8 ± 0.6	0.55 ± 0.03		0	1
125.9 ± 0.6		0.057± 0.015	>0	
127.1 ± 0.6	0.28 ± 0.03		0	2
128.1 ± 0.6	0.46 ± 0.03		0	2
131.4 ± 0.7		0.09 ± 0.02	>0	
133.1 ± 0.7	0.40 ± 0.03		0	2
134.1 ± 0.7	0.26 ± 0.03		0	1
135.8 ± 0.7	0.70 ± 0.05		0	2
136.7 ± 0.7	0.71 ± 0.05		0	2
140.2 ± 0.7	0.16 ± 0.03		0	2
142.1 ± 0.8		0.15 ± 0.03	>0	
142.7 ± 0.8	0.15 ± 0.03		0	2
146.2 ± 0.8		≃0.017	>0	
147.9 ± 0.8	0.17 ± 0.03		0	2
149.4 ± 0.8	0.28 ± 0.03		0	1
151.1 ± 0.8	0.70 ± 0.05		0	1
152.7 ± 0.8	0.40 ± 0.04		0	2

For 35 keV $\leq E_n \leq$ 85 keV:

$S'_{J=2} = 1.42 \times 10^{-4}$

$S'_{J=1} = 4.8 \times 10^{-4}$

a = 6.12 fm

For 85 keV $\leq E_n \leq$ 153 keV:

$S'_{J=2} = 1.9 \times 10^{-4}$

$S'_{J=1} = 3.2 \times 10^{-4}$

a = 6.56 fm

Table III

The resonance parameters of ^{65}Cu

E_o (keV)	Γ_n (keV)	$g\Gamma_n$ (keV)	ℓ	J
34.84 ± 0.09	0.34 ± 0.01		0	2
34.98 ± 0.09		0.02 ± 0.01	>0	
39.57 ± 0.10	0.35 ± 0.01		0	1
40.96 ± 0.10	0.03 ± 0.01		0	2
43.09 ± 0.12	0.15 ± 0.01		0	1
43.78 ± 0.13		0.02 ± 0.01	>0	
44.20 ± 0.13	0.04 ± 0.01		0	1
45.74 ± 0.14	0.04 ± 0.01		0	1
46.65 ± 0.14	≃0.01		0	2
47.55 ± 0.14	0.04 ± 0.01		0	1
50.37 ± 0.16	0.08 ± 0.01		0	1
53.42 ± 0.17	0.14 ± 0.01		0	1
54.34 ± 0.18	0.02 ± 0.01		0	2
54.70 ± 0.18		≃0.01	>0	
56.32 ± 0.19	0.03 ± 0.01		0	2
57.05 ± 0.19	0.06 ± 0.01		0	1
57.7 ± 0.2	0.26 ± 0.01		0	1
62.0 ± 0.2	0.36 ± 0.02		0	1
64.4 ± 0.2	0.10 ± 0.01		0	2
65.2 ± 0.2	0.50 ± 0.02		0	1
67.01 ± 0.24	0.30 ± 0.02		0	2
68.06 ± 0.24	0.11 ± 0.01		0	1
69.44 ± 0.26	0.24 ± 0.01		0	1
72.8 ± 0.3	0.60 ± 0.02		0	1
73.9 ± 0.3		0.02 ± 0.01	>0	
74.4 ± 0.3	0.76 ± 0.02		0	1
75.9 ± 0.3	0.06 ± 0.01		0	1
78.6 ± 0.3	0.17 ± 0.01		0	1
82.3 ± 0.3	0.64 ± 0.02		0	1
82.4 ± 0.3		0.02 ± 0.01	>0	
84.15 ± 0.35	0.07 ± 0.01		0	2
86.3 ± 0.4	0.22 ± 0.02		0	2
88.0 ± 0.4	0.02 ± 0.01		0	2
89.5 ± 0.4	0.08 ± 0.01		0	2
94.3 ± 0.4	0.06 ± 0.01		0	2
98.3 ± 0.4	0.36 ± 0.02		0	1
99.4 ± 0.5	0.13 ± 0.02		0	2
104.8 ± 0.5	0.06 ± 0.01		0	2
105.5 ± 0.5	0.085 ± 0.015		0	1
106.8 ± 0.5	0.75 ± 0.03		0	2
107.8 ± 0.5	0.36 ± 0.03		0	1
111.5 ± 0.5		0.03 ± 0.01	>0	
114.5 ± 0.6		0.02 ± 0.01	>0	
117.3 ± 0.6	0.57 ± 0.03		0	1
119.1 ± 0.6	0.24 ± 0.03		0	2

Table III

The resonance parameters of ^{65}Cu (continued)

E_o (keV)	Γ_n (keV)	$g\Gamma_n$ (keV)	ℓ	J
121.8 ± 0.6	0.09 ± 0.02		0	2
123.4 ± 0.6	0.69 ± 0.04		0	2
126.6 ± 0.6	0.06 ± 0.02		0	2
130.9 ± 0.7	0.11 ± 0.02		0	1
131.9 ± 0.7	0.27 ± 0.03		0	2
133.2 ± 0.7	0.39 ± 0.03		0	1
135.8 ± 0.7	0.49 ± 0.04		0	2
140.0 ± 0.7	0.23 ± 0.02		0	2
144.1 ± 0.8	0.13 ± 0.02		0	1
149.1 ± 0.8	0.56 ± 0.05		0	2

For 34 keV $\leq E_n \leq$ 80 keV:

$S'_{J=2} = 2.0 \times 10^{-4}$

$S'_{J=1} = 0.8 \times 10^{-4}$

a = 7.45 fm

For 80 keV $\leq E_n \leq$ 156 keV:

$S'_{J=2} = 5.54 \times 10^{-4}$

$S'_{J=1} = 2.22 \times 10^{-4}$

a = 7.6 fm

Table IV

The s-wave strength functions

Target Nucleus	J	ΔE (keV)	$\bar{D}$ (keV)	$S \times 10^{-4}$	
^{63}Cu	1	35-153	5.12	1.80 ± 0.52	1.56 ± 0.8 [2]
	2	35-153	3.57	1.78 ± 0.43	2.6 ± 1.0 [2]
	1,2	35-153	2.06	1.80 ± 0.37	2.7 ± 0.8 [1]
^{65}Cu	1	35-156	5.05	1.90 ± 0.54	1.0 ± 0.5 [2]
	2	35-156	5.51	1.22 ± 0.36	1.72 ± 0.7 [2]
	1,2	35-156	2.58	1.51 ± 0.31	1.50 ± 0.5 [1]

FIGURE CAPTIONS

Fig. 1-2: (below): - The transmission data and R-matrix fit for the 0.056 nuclei/barn copper-oxide sample, enriched in ^{63}Cu, vs. neutron energy.

(above): - Resolution broadened, total cross-section of the pure isotope ^{63}Cu computed from the R-matrix parameters.

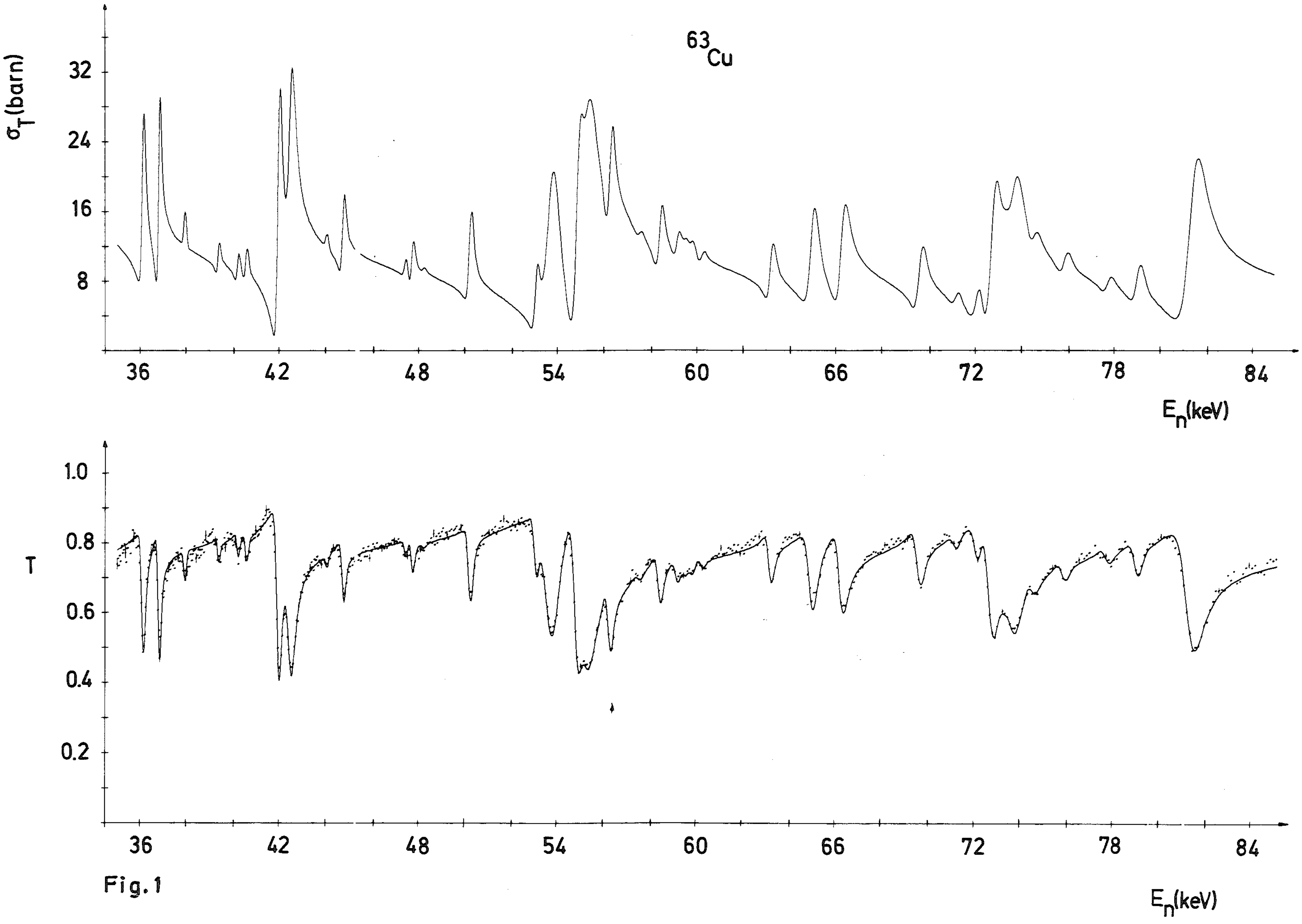
Fig. 3-4: (below): - The transmission data and R-matrix fit for 0.050 nuclei/barn copper-oxide sample, enriched in ^{65}Cu vs. neutron energy.

(above): - Resolution broadened, total cross-section of the pure isotope ^{65}Cu computed from the R-matrix parameters.

Fig. 5-8: Integral distributions of reduced neutron widths for s-wave resonances with spin 1 and 2 of ^{63}Cu and ^{65}Cu, respectively.

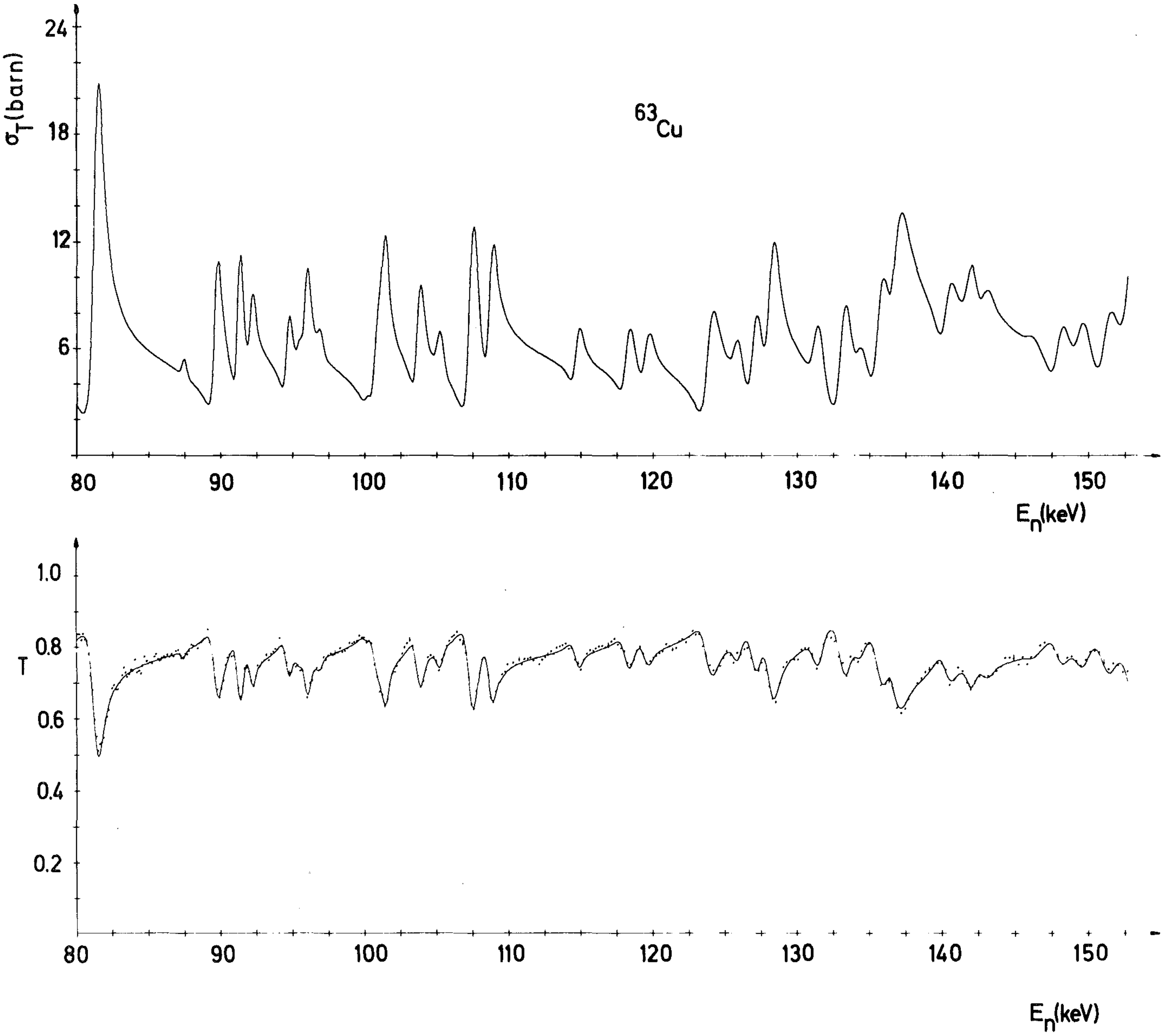
Fig. 9: Differential distribution of the s-wave resonance level spacings of ^{63}Cu and ^{65}Cu.

Fig. 10: Total cross section data of ^{65}Cu in the neutron energy region 150-260 keV.



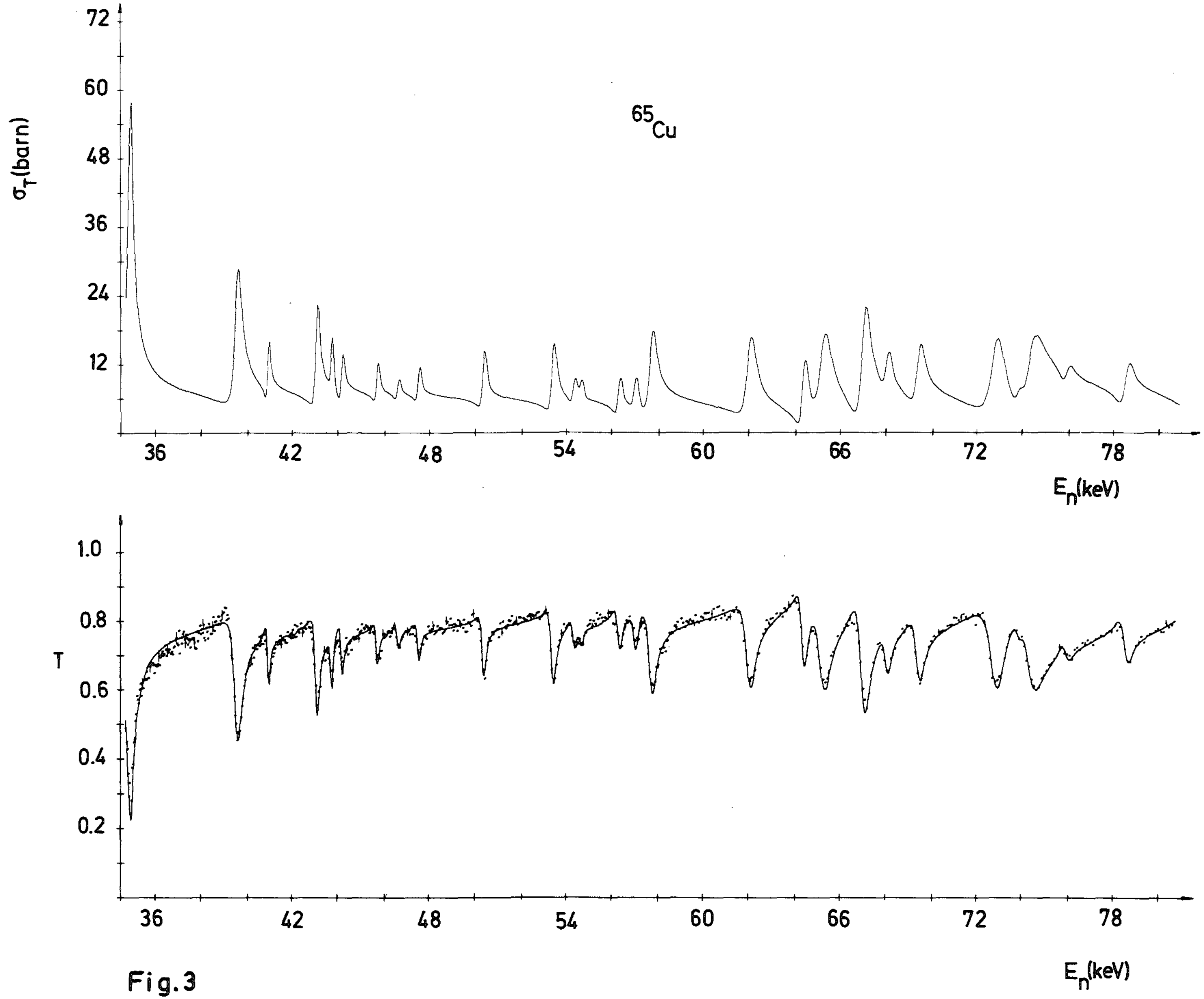
^{63}Cu
σ_T(barn)
32
24
16
8
36
42
48
54
60
66
72
78
84
E_n(keV)
T
1.0
0.8
0.6
0.4
0.2
36
42
48
54
60
66
72
78
84
E_n(keV)

Fig.1



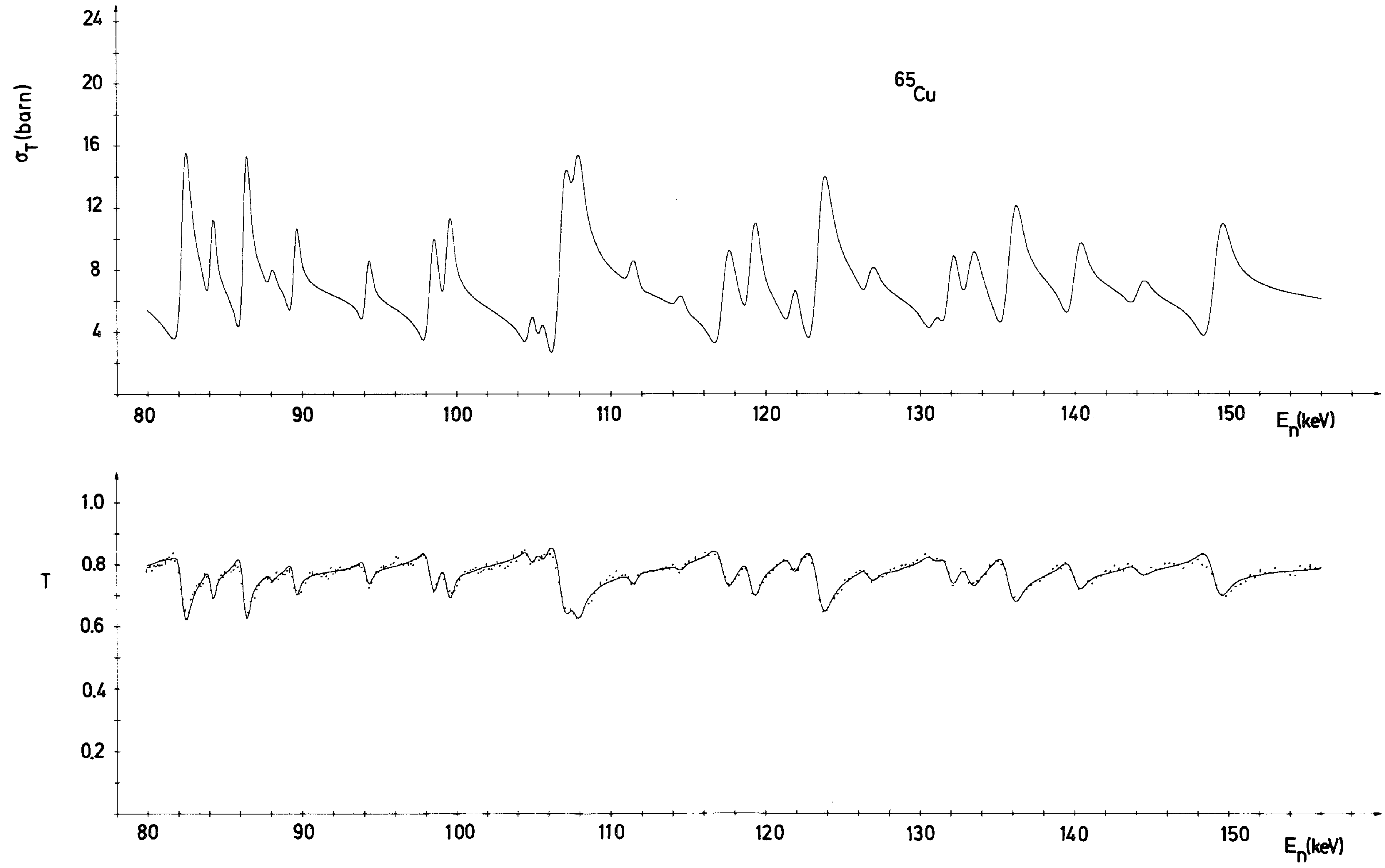
24
18
12
6
σ_T(barn)
^{63}Cu
80
90
100
110
120
130
140
150
E_n(keV)
1.0
0.8
T
0.6
0.4
0.2
80
90
100
110
120
130
140
150
E_n(keV)

Fig.2



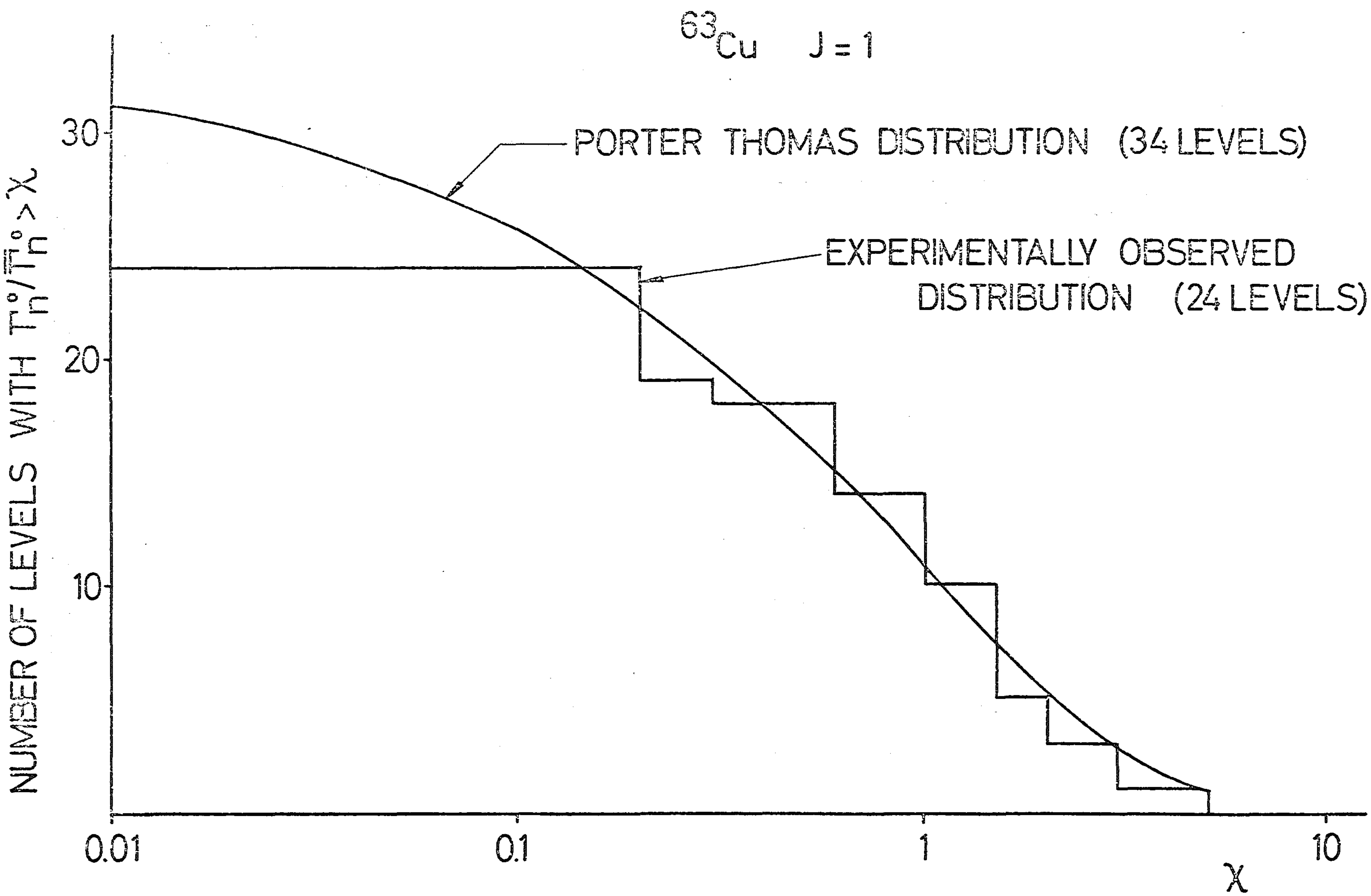
65Cu
σT(barn)
72
60
48
36
24
12
36
42
48
54
60
66
72
78
En(keV)
T
1.0
0.8
0.6
0.4
0.2
36
42
48
54
60
66
72
78
En(keV)

Fig.3



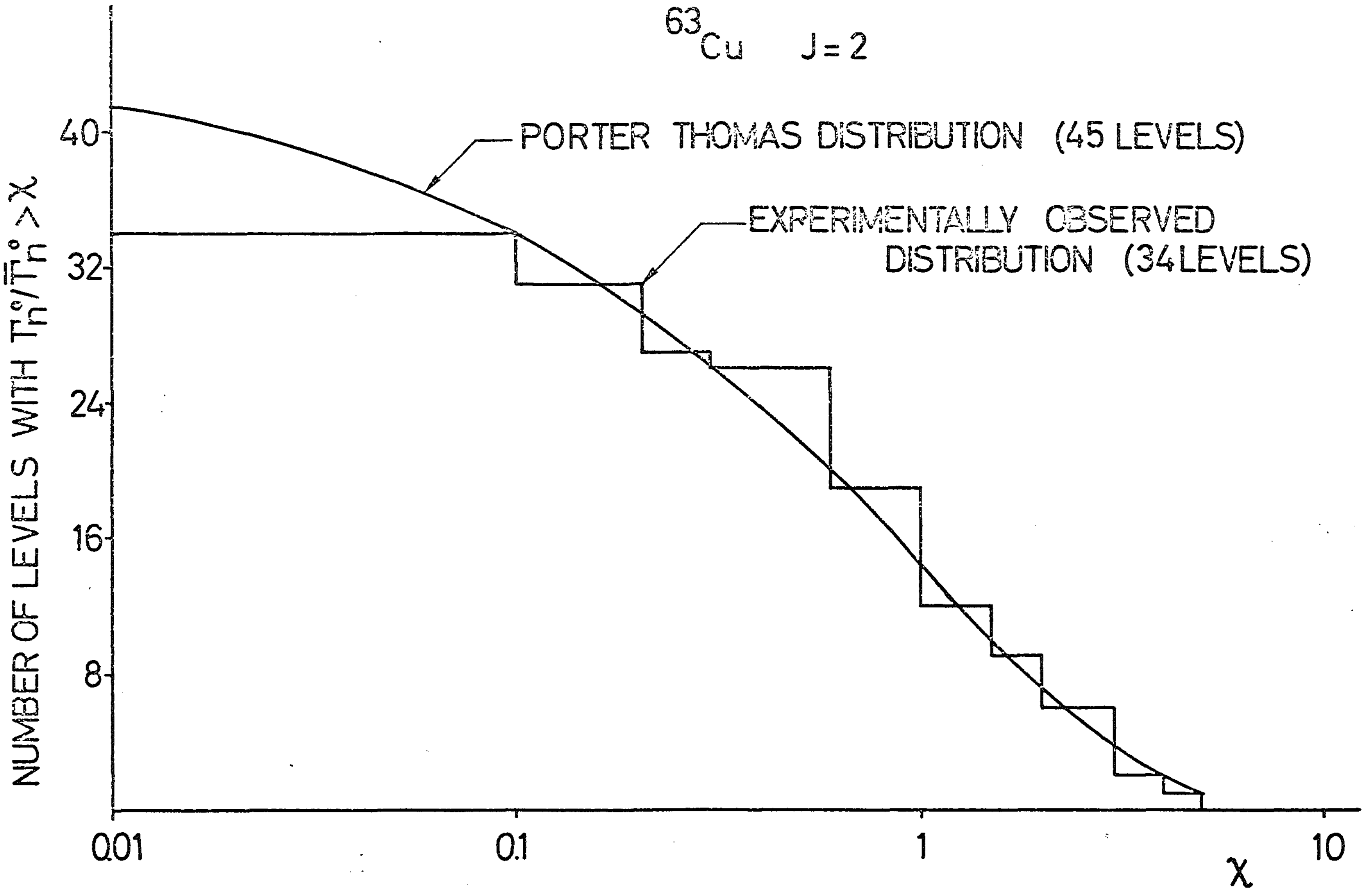
^{65}Cu
σ_T (barn)
24
20
16
12
8
4
80
90
100
110
120
130
140
150
E_n(keV)
T
1.0
0.8
0.6
0.4
0.2
80
90
100
110
120
130
140
150
E_n(keV)

Fig. 4



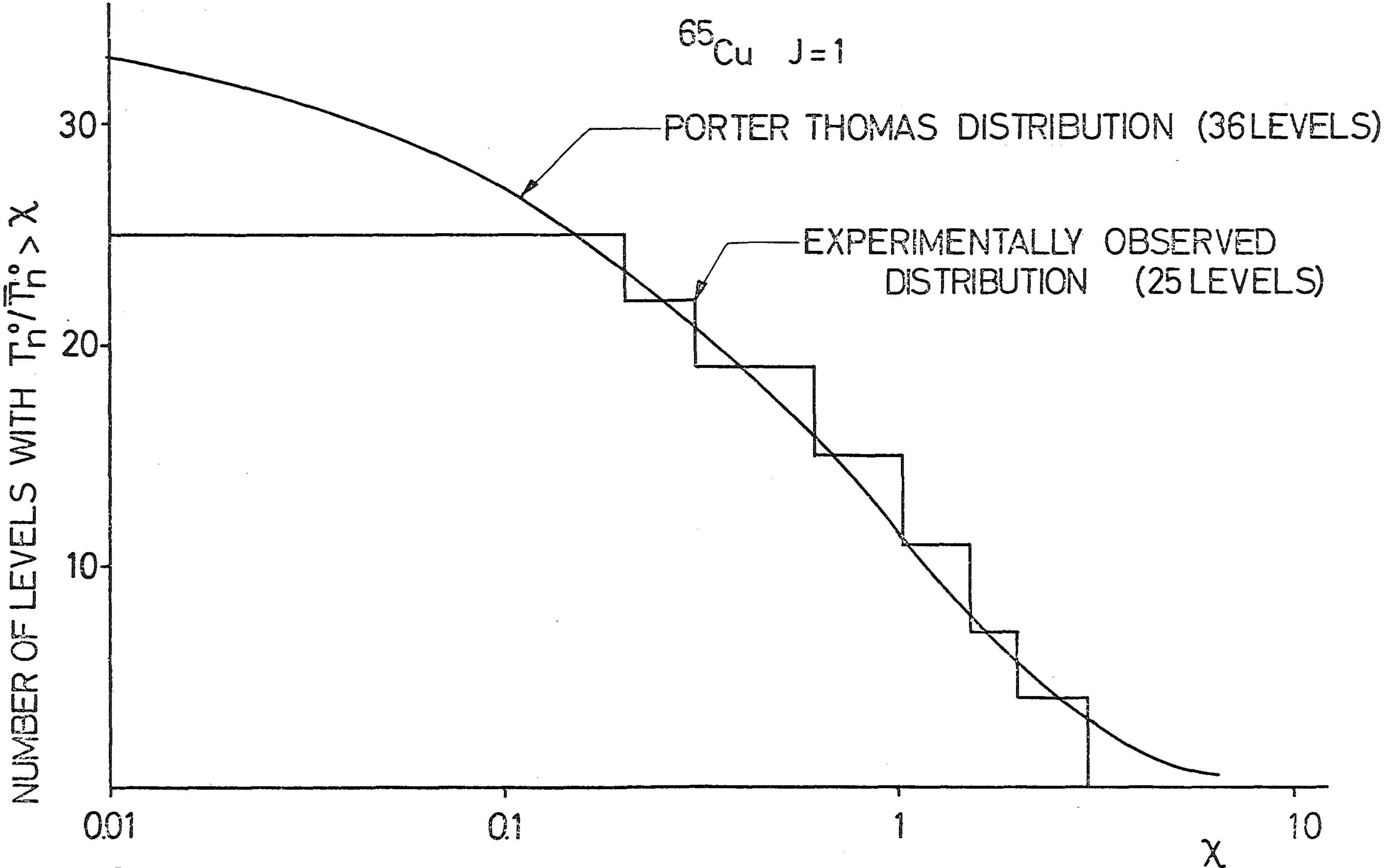
^{63}Cu J = 1
PORTER THOMAS DISTRIBUTION (34 LEVELS)
EXPERIMENTALLY OBSERVED DISTRIBUTION (24 LEVELS)
NUMBER OF LEVELS WITH $\Gamma_n^o/\bar{\Gamma}_n^o > \chi$
30
20
10
0.01
0.1
1
10
χ

Fig.5



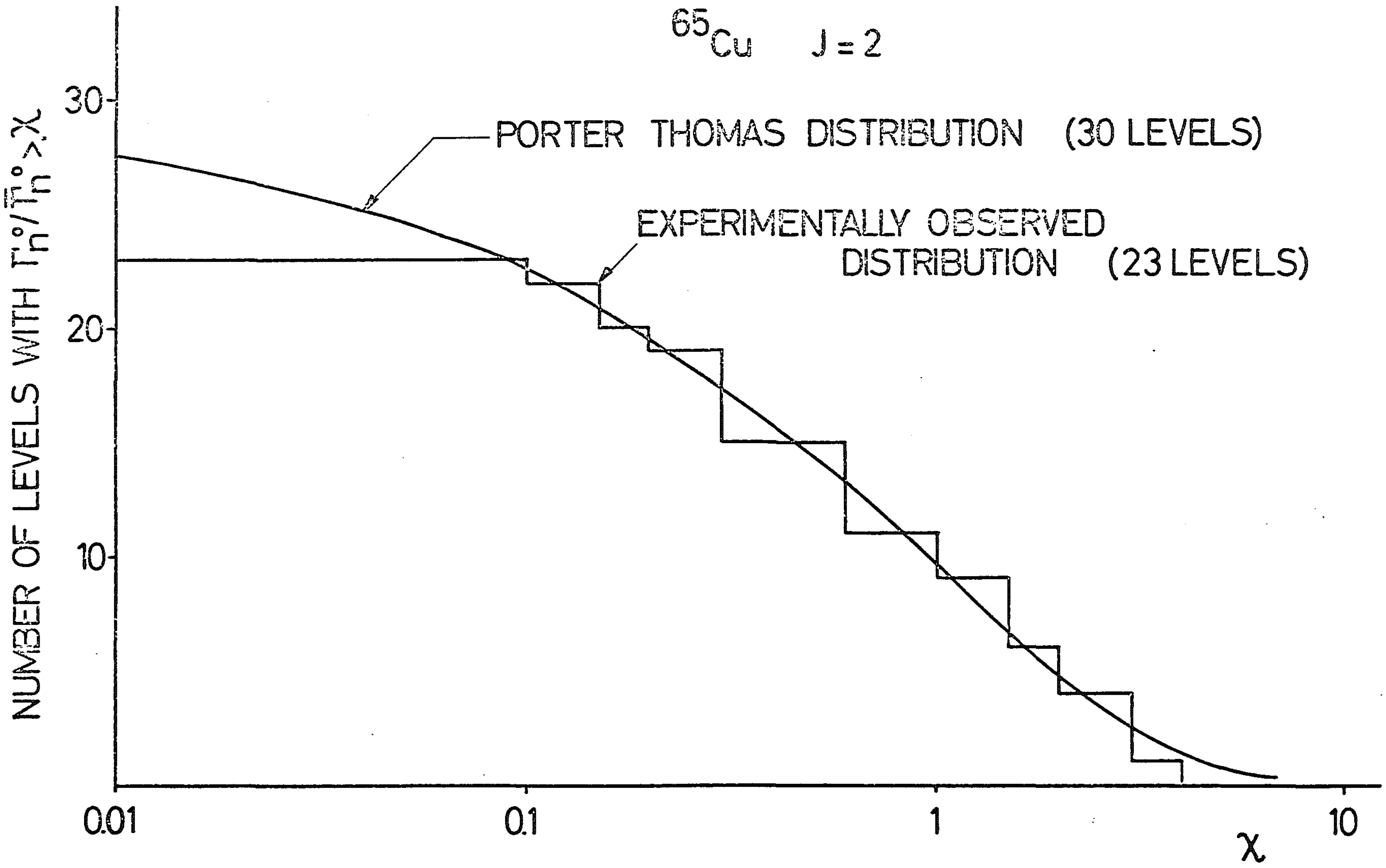
63Cu J = 2
PORTER THOMAS DISTRIBUTION (45 LEVELS)
EXPERIMENTALLY OBSERVED DISTRIBUTION (34 LEVELS)
NUMBER OF LEVELS WITH Γn°/Γ̄n° > χ
40
32
24
16
8
0.01
0.1
1
10
χ

Fig. 6



65Cu J=1
PORTER THOMAS DISTRIBUTION (36 LEVELS)
EXPERIMENTALLY OBSERVED DISTRIBUTION (25 LEVELS)
NUMBER OF LEVELS WITH Γn°/Γ̄n° > χ
30
20
10
0.01
0.1
1
10
χ

Fig.7



^{65}Cu J = 2
PORTER THOMAS DISTRIBUTION (30 LEVELS)
EXPERIMENTALLY OBSERVED DISTRIBUTION (23 LEVELS)
NUMBER OF LEVELS WITH $\Gamma_n^\circ/\bar{\Gamma}_n^\circ > x$
30
20
10
0.01
0.1
1
10
x

Fig. 8

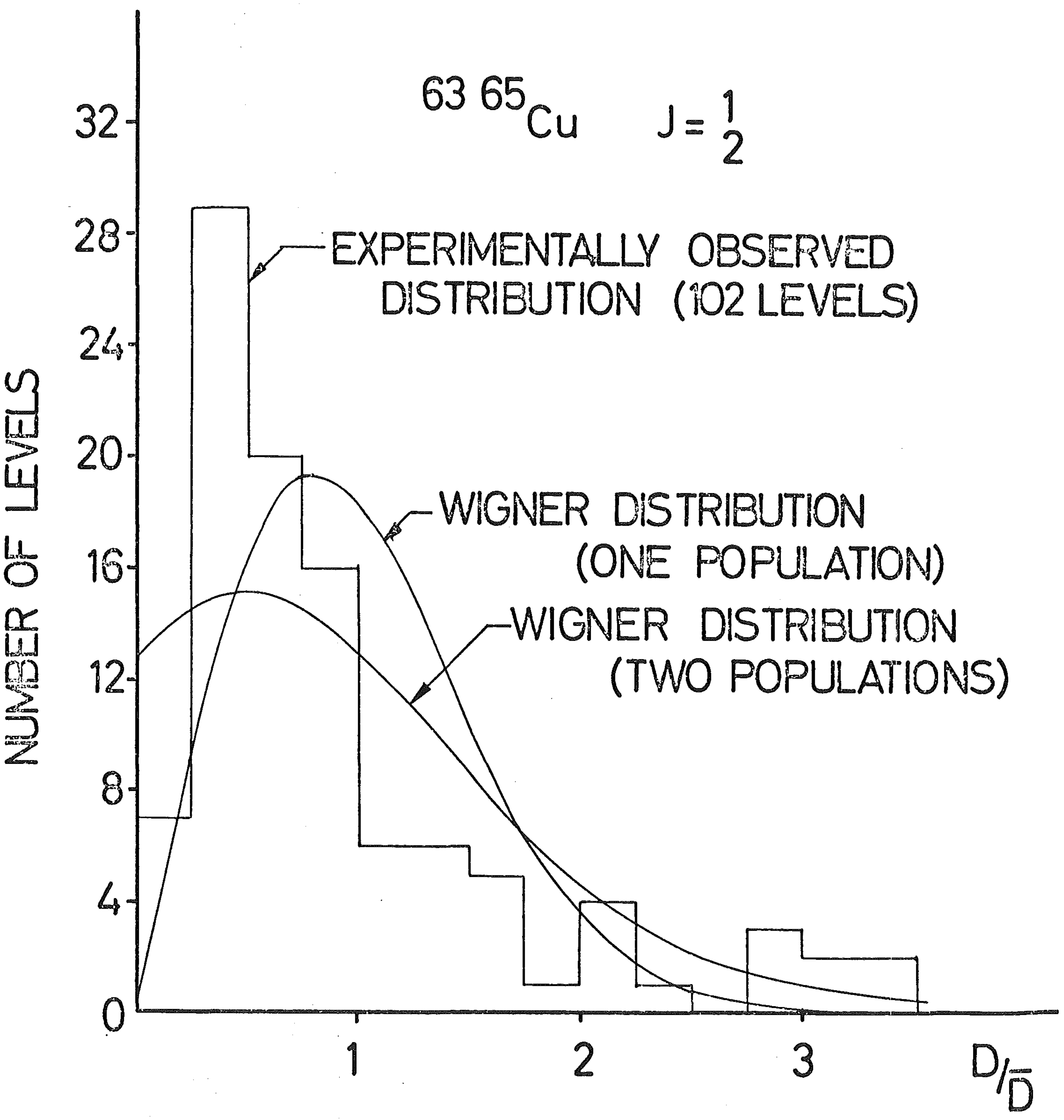

63 65Cu J = 1/2
EXPERIMENTALLY OBSERVED DISTRIBUTION (102 LEVELS)
WIGNER DISTRIBUTION (ONE POPULATION)
WIGNER DISTRIBUTION (TWO POPULATIONS)
NUMBER OF LEVELS
0
4
8
12
16
20
24
28
32
1
2
3
D/D̄

Fig.9

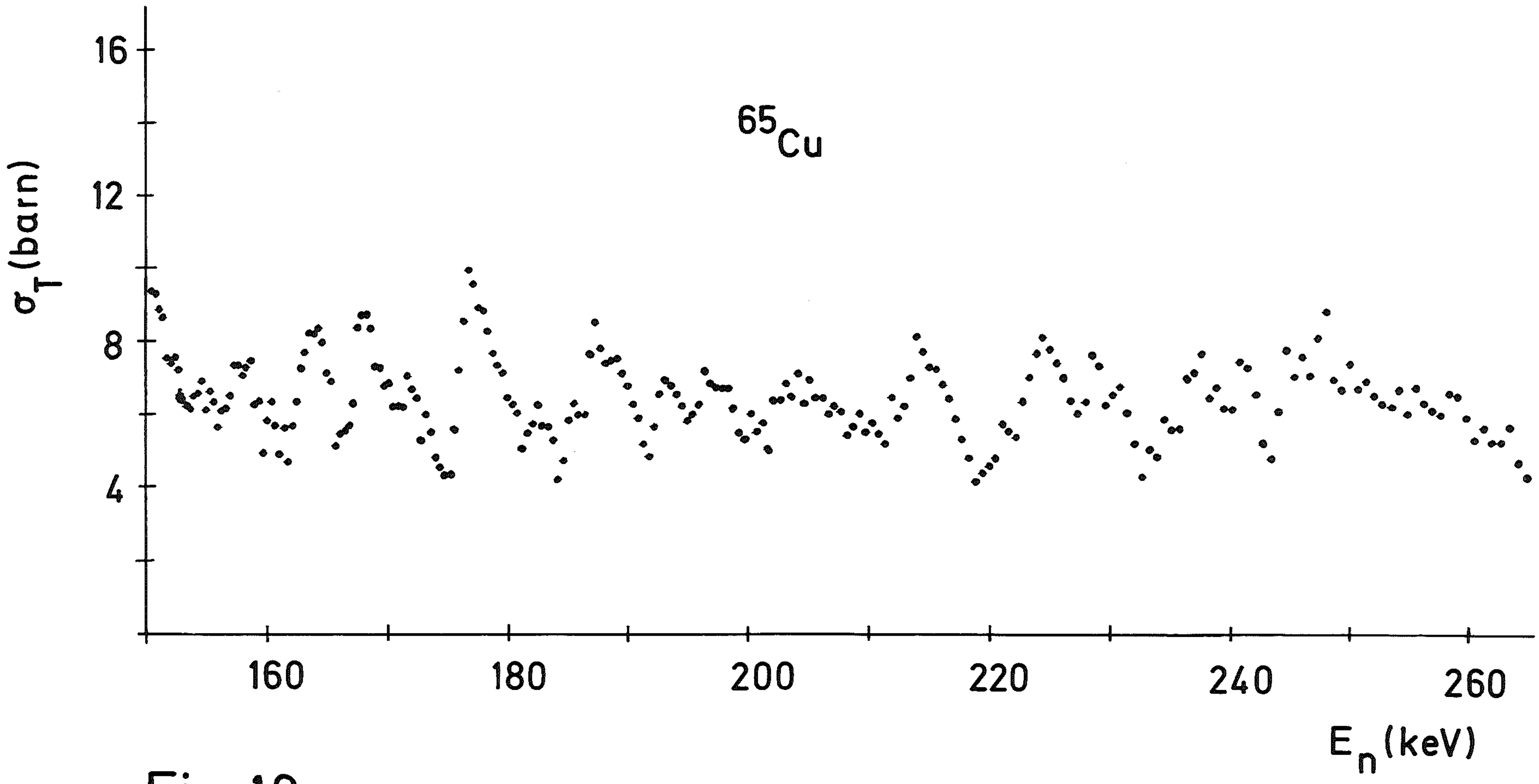


Fig. 10