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A STUDY OF NEUTRON RESONANCES OF VANADIUM AND MANGANESE

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Abstract: Total neutron cross sections up to about 200 keV have been measured for vanadium and manganese. A multi-level formula was employed to compute the resonance parameters. Spins were assigned to 21 levels in vanadium and 42 in manganese.

The distribution of level width obeys a Porter-Thomas distribution only in the case of manganese; possible reasons for the deviations observed in vanadium are proposed.

The most probable strength functions were computed as $(8.2^{+2.2}_{-1.9}) \cdot 10^{-4}$ for vanadium and $(3.1^{+0.9}_{-0.7}) \cdot 10^{-4}$ for manganese.

For both nuclei no spin dependence of the strength function is found; unfortunately the statistical uncertainty of the strength functions for different spin values cannot exclude a $(2J+1)$ dependence. In the case of vanadium it can be shown that intermediate structure effects may influence very strongly the result for the spin dependence of the strength function in different energy intervals.

For manganese, a spin cut-off parameter of $2.5^{+0.7}_{-0.3}$ from the reasonance parameters was deduced.

1. Introduction

Total neutron cross sections in the keV region are of considerable interest for the theory of nuclear reactions. Nevertheless, the existing data are still quite unsatisfactory due to the difficulties of high-resolution spectroscopy in this energy range. Most experimental data on s-wave neutron strength functions in the medium-mass region are based on a small number of resonance parameters measured over a limited energy range only. As the neutron strength function must be considered as a statistical property of the nucleus, these determinations suffer from large uncertainties and might be seriously affected by an intermediate structure.

To get reliable values for the strength function, it is not only necessary to determine a sufficient number of resonance parameters but also to do this over an energy range large enough to average out any possible intermediate structure effects; this is especially important if the spin dependence of the strength function is to be investigated, as doorway states might cause accumulation of resonances with the same spin at certain energies.

A study of a large number of resonances in a particular isotope would further yield valuable information on the statistical properties of excited levels and allow the

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direct determination of the spin cut-off parameter appearing in the statistical model of the nucleus.

Firk *et al.* [1]), have measured the parameters of six resonances of vanadium up to 25 keV. Measurements at higher energies were performed with the cyclotron of the Columbia University by Garg *et al.* [2]). Spin values have been assigned for six resonances between 20 keV and 100 keV by these workers. The cross section between 30 keV and 70 keV was also measured by Morgenstern *et al.* [3]) using the linear accelerator at Saclay. No spins were given in this case, only the resonance energies were tabulated.

Manganese too has been investigated by the latter two groups. The Columbia group gives spin values for 16 resonances with energies up to 60 keV, while the Saclay group determined the spin values of 14 resonances between 10 keV and 74 keV.

It was the intention of this work to measure the cross sections of vanadium and manganese up to about 200 keV with sufficient precision to allow the determination of all major resonances in the energy range covered.

2. Experimental method

The total neutron cross section was measured by the time-of-flight method employing a 3 MeV van de Graaff accelerator producing 1 nsec pulses. The neutrons were generated in a thick lithium target by the (p, n) reaction. Up to about 60 keV, a boron slab, viewed by four scintillation crystals perpendicular to the neutron beam, was used together with a flight path of 6.2 m. At higher energies a proton recoil detector at a distance of 10 m from the target was employed. A more detailed discussion of our spectrometer has been given elsewhere [4]).

The time resolution of the experimental set-up with the boron-slab detector was determined as a function of the neutron energy by measuring the time width of the 478 keV γ-line originated in the lithium target and by taking into account the transit time of the neutrons through the detector volume and the channel width of the analyser. The energy resolution was found to be 0.6 nsec/m at 60 keV. For the proton recoil detector one gets in a similar way a resolution of 0.39 nsec/m at 220 keV.

The time of flight was measured with a digital time coder (HC98 from Intertechnique) with a smallest channel width of 1 nsec and a large time range (4 μsec). Both spectra, with and without sample, were stored in the memory block of a CAE RW 510 computer. The background was estimated during the same measurement by observing the intensity in the time spectrum just above the maximum neutron energy.

For best results, the transmission should be kept between 0.6 and 0.8. To accomplish this, different sample thicknesses were used. In the case of vanadium metal sheets with thicknesses of 1.39×10^{22}, 2.78×10^{22}, 5.55×10^{22} and 11.16×10^{22} atom/cm^2 have been employed. Manganese which was only available as a powder, was placed into aluminium containers. For a comparison measurement, aluminium foils of the same thickness as the container walls were placed in the neutron beam.

Sample thicknesses were in this case 2.18×10^{22}, 4.36×10^{22}, 8.72×10^{22} and 17.44×20^{22} atom/cm^2.

As with a van de Graaff generator, the place of origin of the neutrons is rather well defined, the physical size of the samples could be kept small. A few gram of sample material is quite sufficient, so that with the same setup, separated isotopes can be studied.

3. Analysing technique

For the analysis of the data, only s-wave scattering has been considered. The probability that p-waves contribute appreciably to the cross sections is extremely small due to the minimum of the p-wave strength function near $A = 50$. Furthermore the penetrability for $l = 1$ is such that the existence of resonances broad enough to be resolved experimentally is rather unlikely.

Because both isotopes investigated have rather complex spectra, the multi-level formula which results from the R-matrix theory has been employed [5]). For s-waves, the cross section is given by

$$\sigma = 4\pi\lambda\!\!\!^{-2}\sum_J g_J\left[\sin^2\varphi_J+\frac{\cos 2\varphi_J - x_J\sin 2\varphi_J}{1+x_J^2}\right], \tag{1}$$

with

$$x_J = \frac{1}{\sum_\lambda \Gamma_{\lambda J}/2(E_{\lambda J}-E)}, \tag{2}$$

$$\varphi_J = k\,a(1-R_J), \tag{3}$$

where a is the radius of the nucleus and g_J the spin multiplicity. The widths and resonance energies $\Gamma_{\lambda J}$ and $E_{\lambda J}$ are to be determined from the cross section curve; R_J takes into account the influence of the resonances outside the measured region. It was found that the cross section between the resonance peaks could be better fitted by eq. (1) when a slight energy dependence of R_J was assumed. In eq. (3) therefore the expression

$$R_J = A_J + B_J(E-E_{\mathrm{M}}) + C_J(E-E_{\mathrm{M}})^2 \tag{4}$$

was used with E_{M} the midpoint of the measured energy range. The parameters A_J, B_J and C_J were chosen to give the best fit away from resonance peaks for the complete energy region.

For comparison between the theoretical cross section and the observed results, the finite resolution of the spectrometer has to be taken into account. To achieve this the multi-level formula was folded with the experimental resolution function, assuming the latter to have a Gaussian form.

4. Results

4.1. RESONANCE PARAMETERS

The vanadium data. In fig. 1, the experimental cross section is shown. The solid line

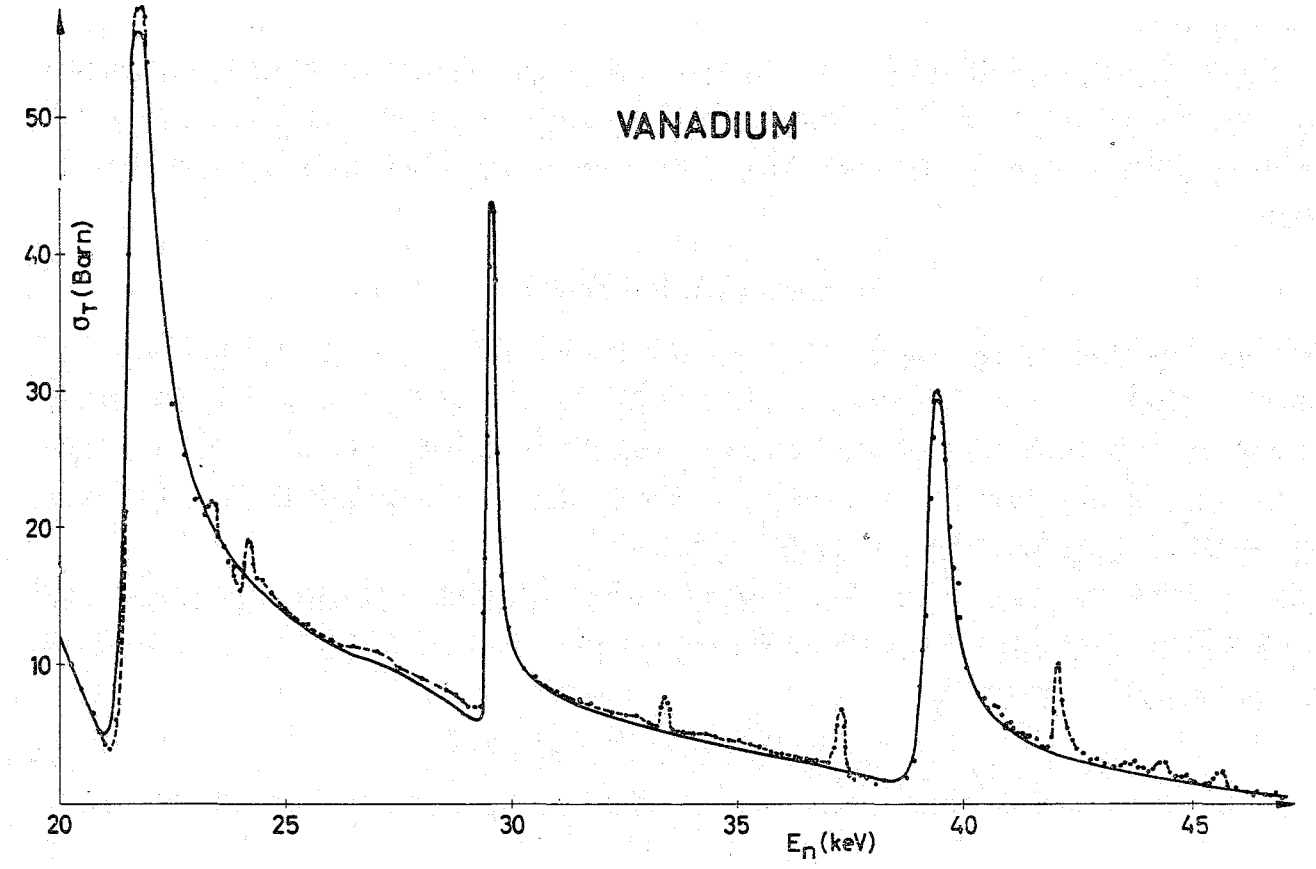
VANADIUM
σ_T (Barn)
50
40
30
20
10
20
25
30
35
40
45
E_n (keV)

Fig. 1a.

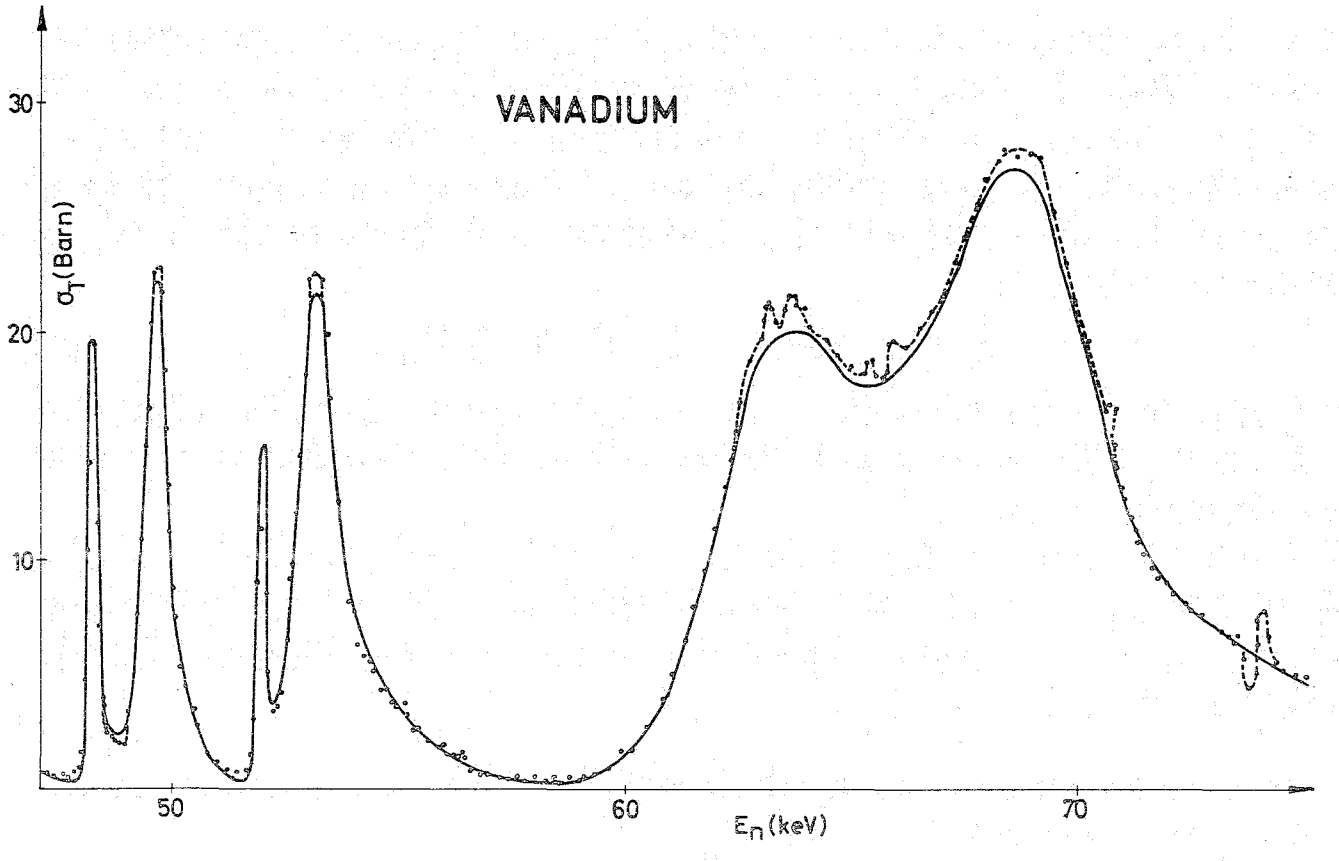
VANADIUM
σ_T (Barn)
30
20
10
50
60
70
E_n (keV)

Fig. 1b.

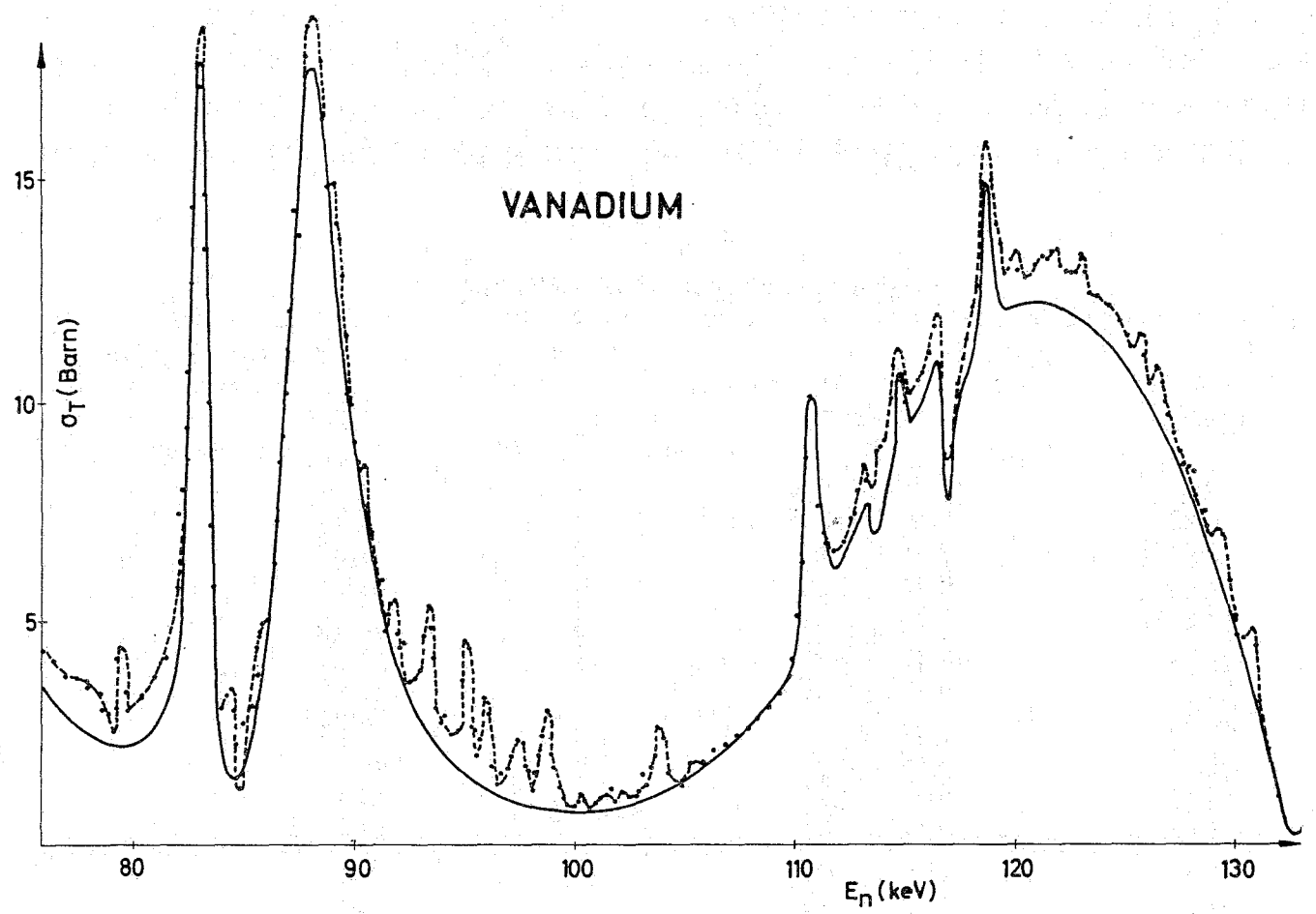

Fig. 1c.

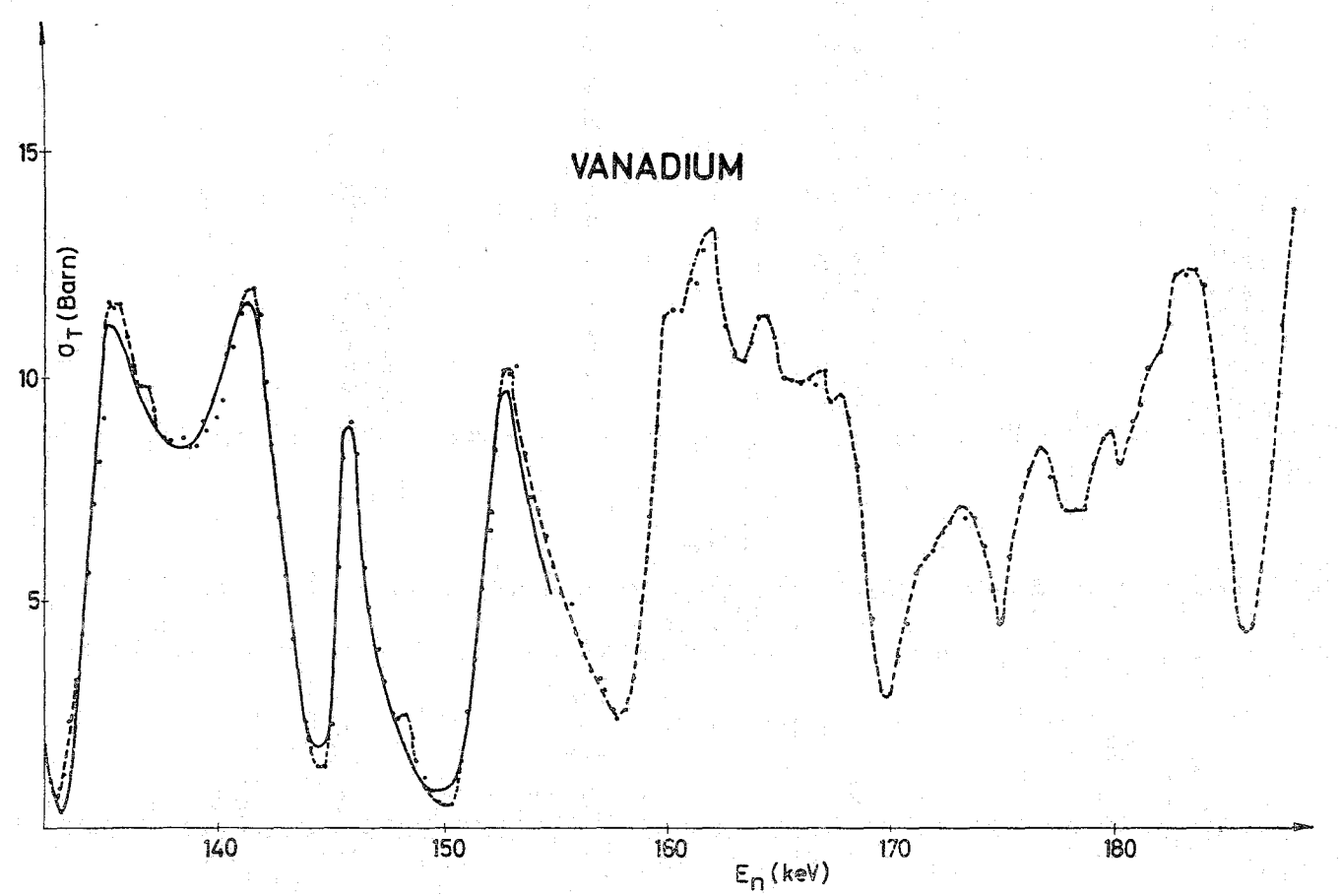

Fig. 1d.

Fig. 1. Total neutron cross section curve for ^{51}V. The solid line represents the multi-level fit.

represents the multi-level formula calculated with the resonance parameters given in table 1. For the non-resonant part, the parameters of table 2 were used in eq. (4). Parameters of 21 resonances above 20 keV have been determined. The results of the Columbia group are given together with ours. Also given are five resonances below

TABLE 1

Resonance parameters of vanadium

Present results			Results of Garg *et al.*	
E(keV)	Γ_n(keV)	J	E(keV)	J
4.17 [a])	0.508 ±0.006	4	4.16	4
6.89 [a])	1.28 ±0.014	3	6.80	3
11.81 [a])	5.5 ±0.05	3	11.68	3
16.60 [a])	0.35 ±0.04	4	16.23	4
17.4 [a])	0.35 ±0.04	4	16.99	3
21.65	0.79 ±0.05	3	21.75	3
29.45	0.191 ±0.02	4	29.63	3
39.3	0.57 ±0.04	3	39.54	
48.15	0.15 ±0.02	4	48.15	
49.55	0.63 ±0.04	3	49.48	
51.95	0.115 ±0.02	4	51.98	
53.0	0.98 ±0.04	3	53.0	
62.9	3.80 ±0.10	3	63.9	3
68.1	4.70 ±0.10	4	68.6	4
83.0	1.20 ±0.05	4	82.6	3
87.6	3.20 ±0.08	4	87.5	4
110.8	0.25 ±0.03	3	110.5	
113.5	0.11 ±0.01	4		
114.8	0.08 ±0.01	3	114.4	
116.6	2.40 ±0.08	4	116.0	
118.7	20.5 ±1.0	4		
118.7	0.13 ±0.02	3	118.5	
134.7	3.20 ±0.15	4	134.2	
141.3	3.60 ±0.15	3	140.6	
145.7	1.50 ±0.10	3	145.5	
152.9	3.50 ±0.15	4	152.7	

[a]) Ref. [1]).

TABLE 2

The influence of the unknown resonances outside the measured range on the phase shift (for vanadium)

		$J = 3$	$J = 4$
$E_M = 90$ keV	A	0.35	−0.15
	B	$5.0 \cdot 10^{-3}$	$7.5 \cdot 10^{-3}$
$E < E_M$	C	$-1.1 \cdot 10^{-4}$	$-1.2 \cdot 10^{-4}$
	A	0.35	−0.15
	B	$5.0 \cdot 10^{-3}$	$7.5 \cdot 10^{-3}$
$E > E_M$	C	$1.18 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$

TABLE 3
Resonance parameters of manganese

Present results			Results of Morgenstern *et al.* [3])		
E(keV)	Γ_n(keV)	J	E(keV)	Γ_n(keV)	J
53.4	0.09±0.01	2	53.28	0.08	2
57.45	0.81±0.03	3	57.38	0.42	3
58.0	0.06±0.01	2	58.06	0.95	2
59.5	0.27±0.02	3	59.48	0.75	2
59.95	0.10±0.01	2			
64.1	1.01±0.05	3	64.13	0.80	3
66.6	0.16±0.02	2	66.46	0.12	3
69.55	0.14±0.02	3	69.47	0.17	2
70.07	0.32±0.02	2	70.0	0.27	3
73.9	0.71±0.04	3	73.88	1.0	2
81.3	0.44±0.03	2			
84.35	1.31±0.05	3			
96.05	0.21±0.02	2			
98.2	0.45±0.04	3			
103.7	0.27±0.02	2			
104.9	1.51±0.06	2			
107.0	0.41±0.04	2			
109.4	1.32±0.13	2			
110.9	1.83±0.15	3			
116.1	0.47±0.03	3			
118.4	0.71±0.04	3			
123.5	0.51±0.05	2			
127.0	2.03±0.20	3			
128.1	1.51±0.15	2			
129.5	1.21±0.15	2			
131.0	0.22±0.03	3			
142.1	0.55±0.06	3			
151.3	0.41±0.08	2			
155.8	1.02±0.10	2			
158.7	0.92±0.05	3			
166.9	0.31±0.05	2			
172.2	1.72±0.15	3			
176.9	0.32±0.03	3			
179.9	0.35±0.05	2			
181.0	0.25±0.05	3			
184.4	1.00±0.15	2			
186.2	2.20±0.20	3			
188.5	0.81±0.10	3			
193.9	0.30±0.03	3			
197.6	0.62±0.05	2			
203.4	2.70±0.30	3			
207.7	2.80±0.30	2			

TABLE 4
The influence of the unknown resonances outside the measured range on the phase shift for manganese

		A	B	C
$E_M = 150$ keV	$E < E_m$	0	$+1.0 \cdot 10^{-3}$	$-4.0 \cdot 10^{-5}$
	$E > E_m$	0	$+1.0 \cdot 10^{-3}$	$+4.0 \cdot 10^{-5}$

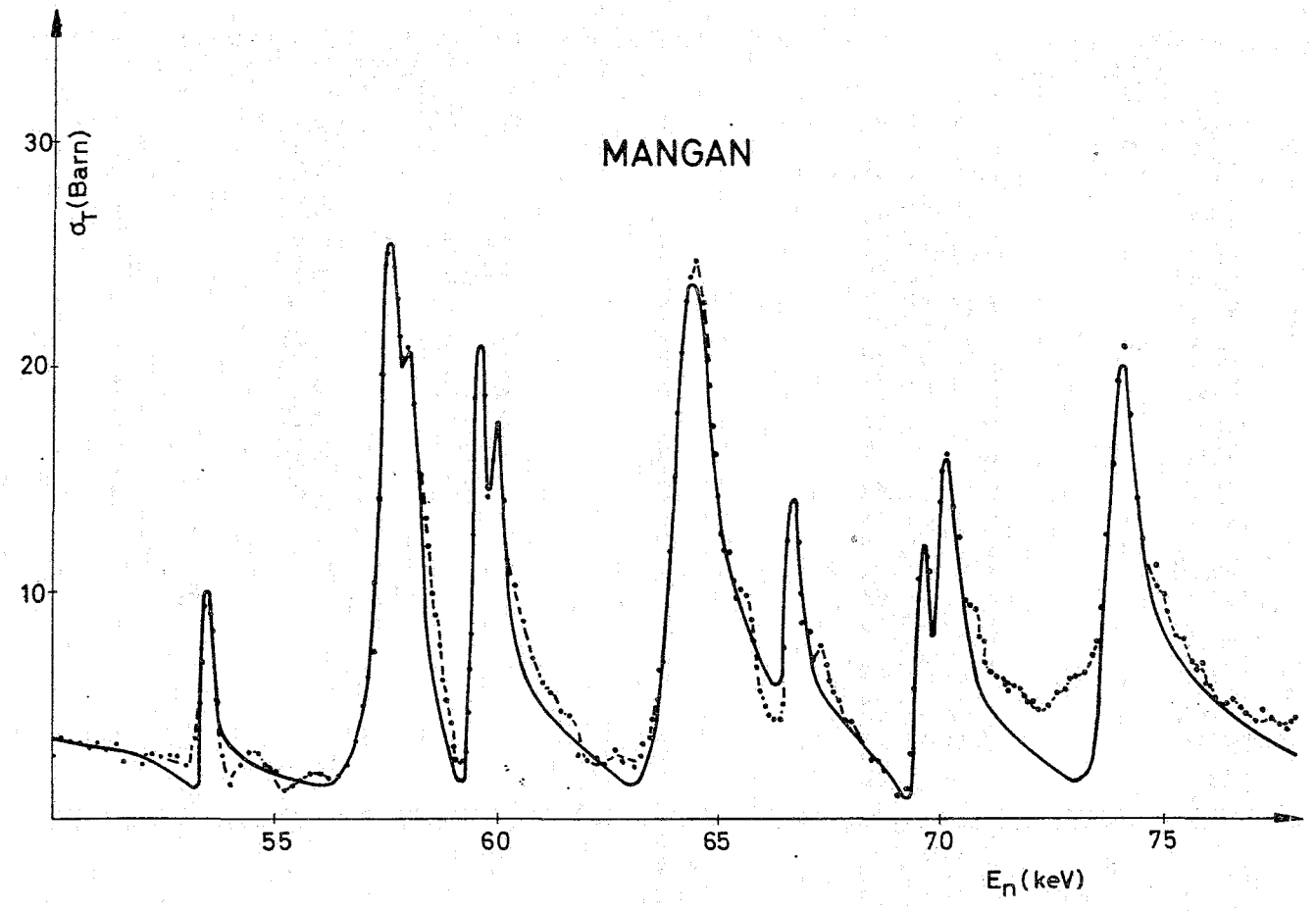
MANGAN
σT(Barn)
30
20
10
55
60
65
70
75
En (keV)

Fig. 2a.

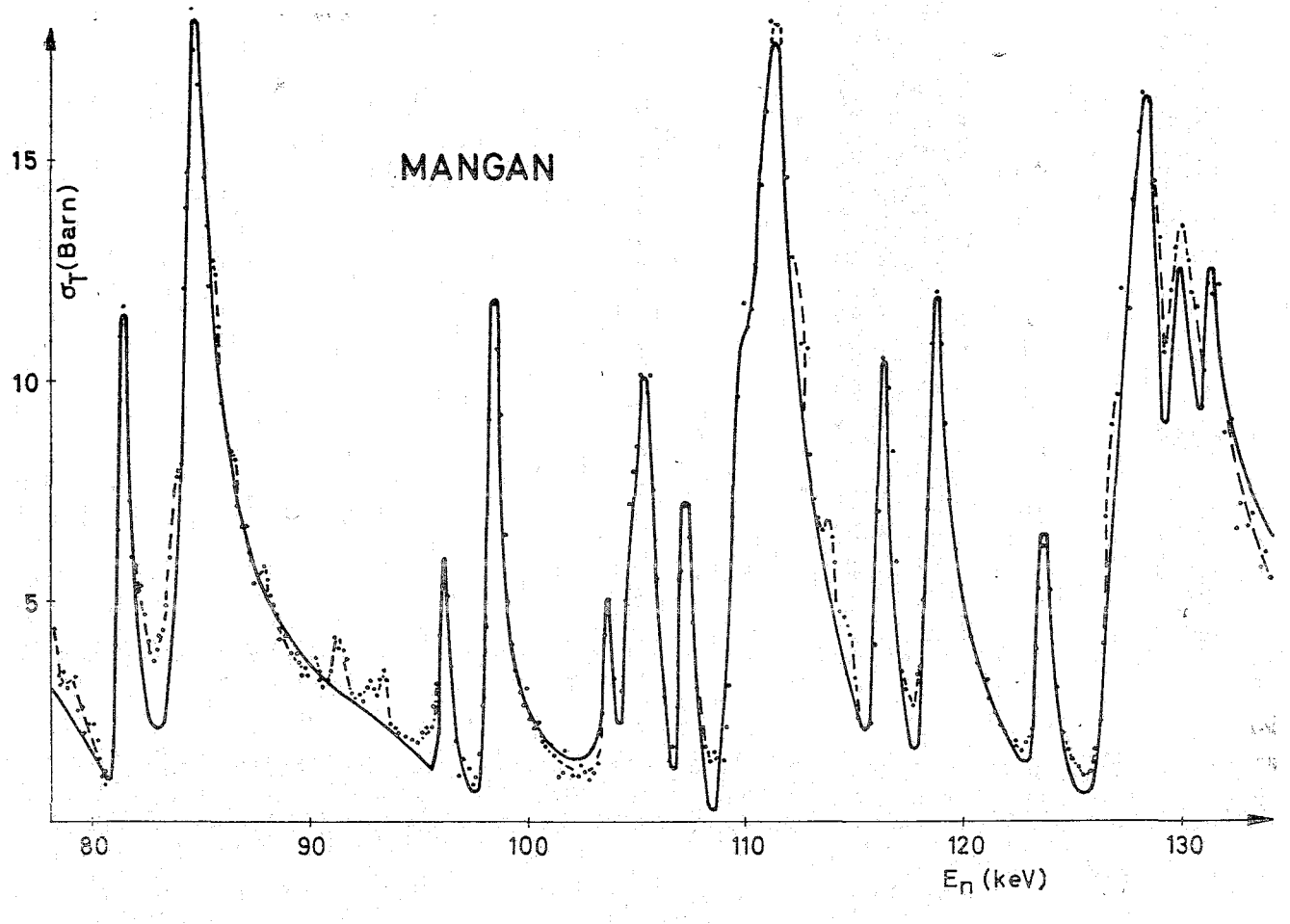
MANGAN
σT(Barn)
15
10
5
80
90
100
110
120
130
En (keV)

Fig. 2b.

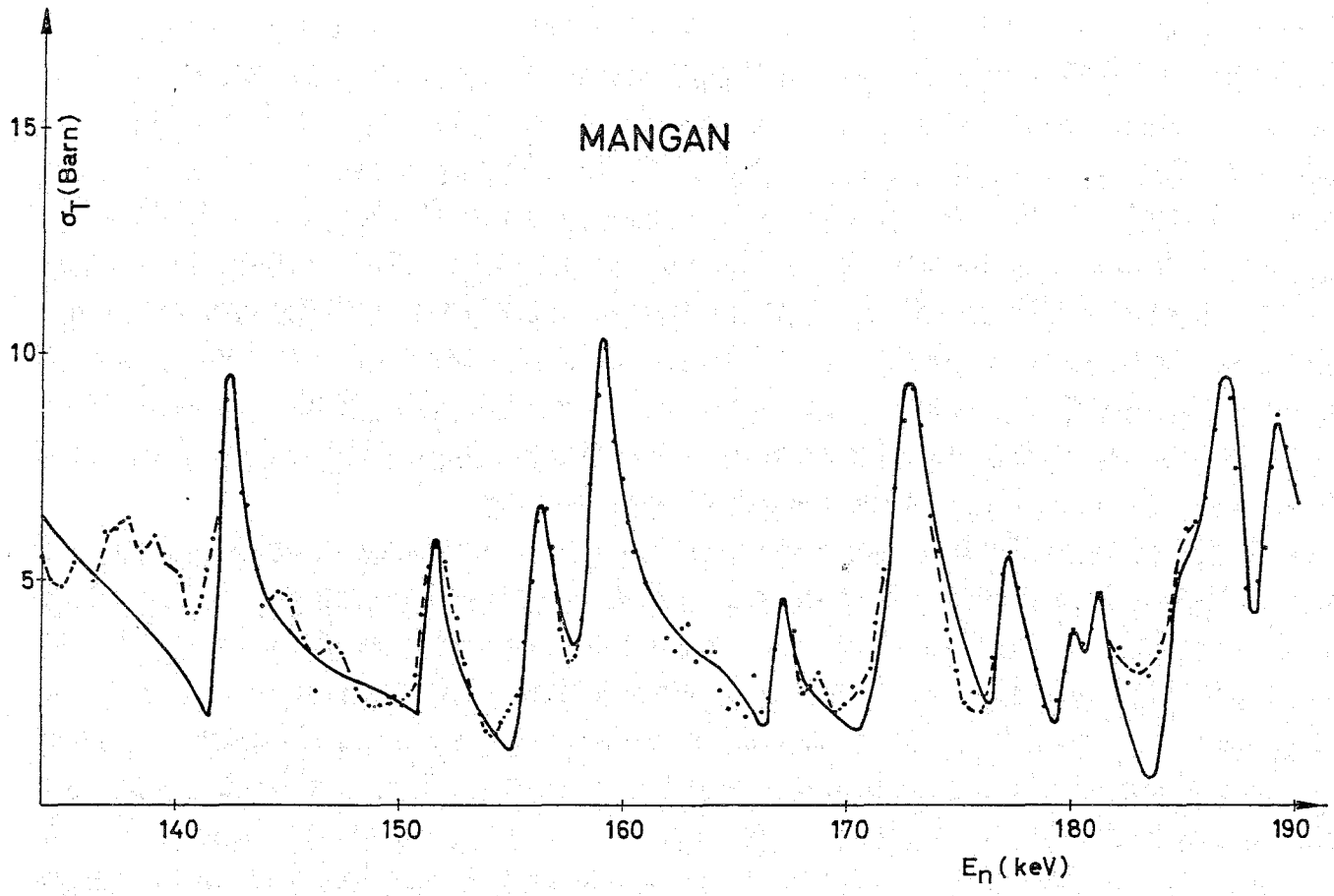

Fig. 2c.

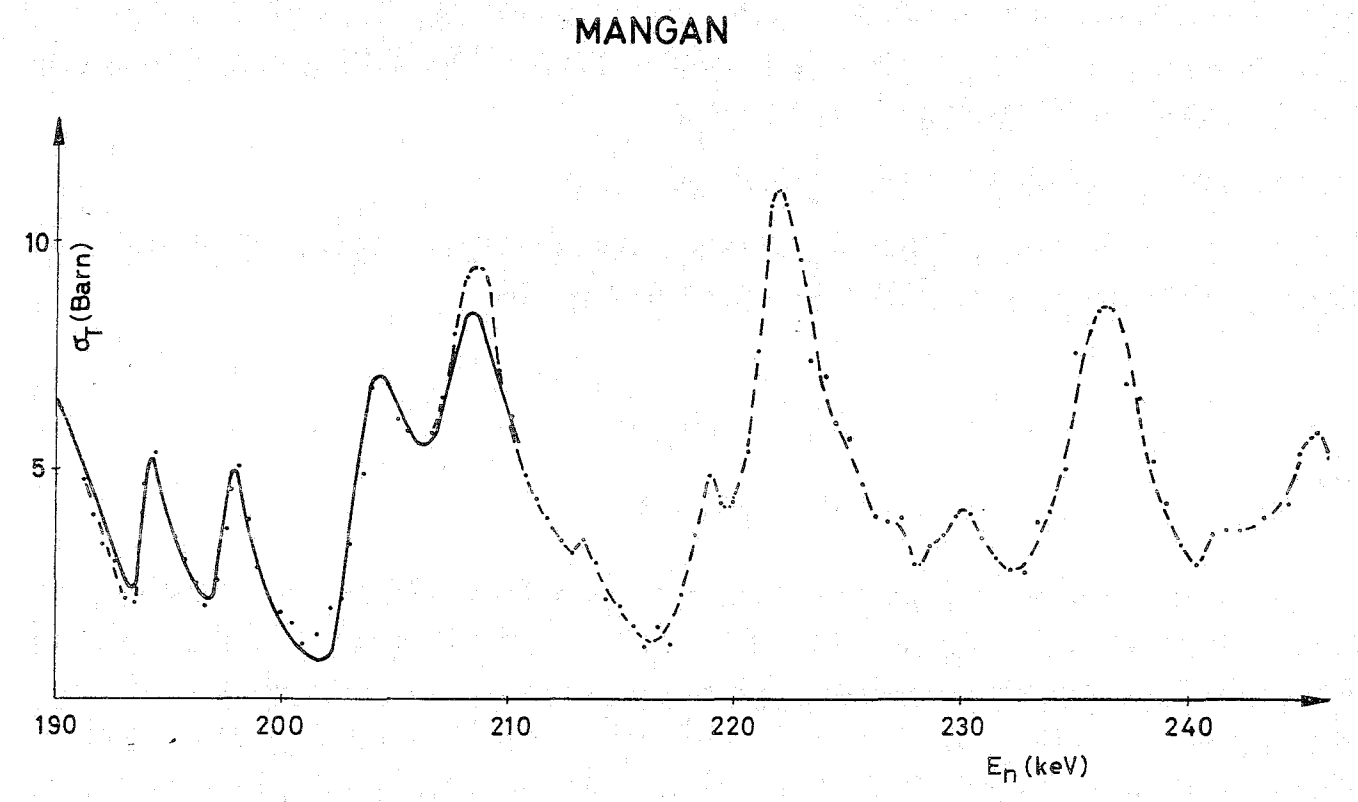

Fig. 2d.

Fig. 2. Total neutron cross section curve for ^{55}Mn. The solid line represents the multi-level fit.

20 keV which were taken from the paper of Firk *et al.* [1]). For the resonance at 29.45 keV, we find a spin disagreement with the result of Garg *et al.* A spin of 3, as stated by them, must lead to interference with the resonance at 21.65 keV and depresses the cross section to about 2.5 b at 29 keV. The observed minimum between these two peaks of 6.3 b can only be explained by assuming a spin of 4. A further discrepancy is found near 84 keV. Here Garg *et al.* assigned different spins to the two resonances at 83.0 keV and 87.6 keV. The marked interference dip between these two peaks, however, show quite clearly that both resonances must have the same spin. A pure superposition of the two resonances, which would result from different spins, yield a minimum cross section between these two peaks of approximately 6 b, which is about three times as large as the measured cross section.

4.1.2. *The manganese data.* The results for manganese are given in fig. 2 and tables 3 and 4. Parameters of altogether 42 resonances have been computed, 33 of which are determined for the first time. The resonance parameters as given by the Saclay group are included in table 3 for comparison. The agreement is not very good. At 58 keV, we find only a small resonance superposed on a large resonance at 57.45 keV, while Morgenstern *et al.* found a large resonance at 58.06 keV superposed on a smaller one at 57.38 keV. They therefore assumed that the sharp minimum at 59 keV is a result of interference between the resonances at 58 keV and 59.5 keV and assigned a spin value of 2 to the latter peak. From our results, however, it is obvious that the resonance at 59.5 keV interferes with the one at 57.45 keV, therefore spin of 3 must be assigned to that level. Superposed on this peak is a smaller resonance at 59.95 keV, which has not been noticed before. Furthermore our results show a reversed order of the spin values for the four resonances between 66.6 keV and 73.9 keV. In general the multi-level formula fits the experimental results very well. Deviations at some energies may be explained by unresolved resonances.

4.2. DISTRIBUTION OF REDUCED NEUTRON WIDTHS

Generally it is assumed that the reduced neutron widths with a given spin and parity are distributed to a Porter-Thomas function, viz.

$$P(x) = \frac{1}{(2\pi x)^{\frac{1}{2}}} \, \mathrm{e}^{-\frac{1}{2}x}, \tag{5}$$

where

$$x = \Gamma_{\mathrm{n}}^{0}/\bar{\Gamma}_{\mathrm{n}}^{0}.$$

To test the distribution one has to keep in mind that resonances below a certain width have escaped detection. By assuming the validity of eq. (5), it is possible to estimate the number of missed resonances, if the experimental resolution limit is known. In this connection, the resolution limit must be considered as the smallest width from which parameters can still be found; with the analysing technique employed this is about $\frac{1}{2}$ of the instrumental resolution width.

Applying this separately to the two different spin systems, the results in tables 5

and 6 are obtained for vanadium and manganese, respectively. The number of levels N, the average level distance D, the averaged reduced neutron width $\bar{\Gamma}_n^0$ and the strength function S as computed directly from the resonance parameters are given in the first row. In the second row, the corresponding values after correction for missed levels are tabulated. In table 7 the same parameters are given per spin system assuming no spin dependence.

TABLE 5
Averaged values for vanadium

		N	D(keV)	$\bar{\Gamma}_n^0$(eV)	S (10^{-4})
$J = 3$	without	12	12.6	9.28	7.36
	with "missed level"	14.3	10.6	7.83	7.38
$J = 4$	without	14	11.4	9.5	8.30
	with "missed level"	16.8	9.6	8.0	8.33

TABLE 6
Averaged values for manganese

		N	D(keV)	$\bar{\Gamma}_n^0$(eV)	S (10^{-4})
$J = 2$	without	21	7.72	1.89	2.44
	with "missed level"	46.2	3.42	0.94	2.80
$J = 3$	without	21	7.30	2.63	3.6
	with "missed level"	37.8	3.97	1.51	3.81

TABLE 7
Averaged values for the nucleides ^{51}V and ^{55}Mn independent of the spin

		N	D(keV)	$\bar{\Gamma}_n^0$(eV)	S (10^{-4})
^{51}V	without	26	11.6	9.40	8.05
	with "missed level"	31	9.78	7.90	8.07
^{55}Mn	without	42	7.52	2.26	3.0
	with "missed level"	84	3.78	1.22	3.25

The values for D and $\bar{\Gamma}_n^0$ are changed considerably by including missed levels, while the influence of missed levels on the strength function is small. In the case of vanadium, this correction yields only five unresolved levels, which is unrealistically low, as 27 resonances too small for the determination of the parameters have already

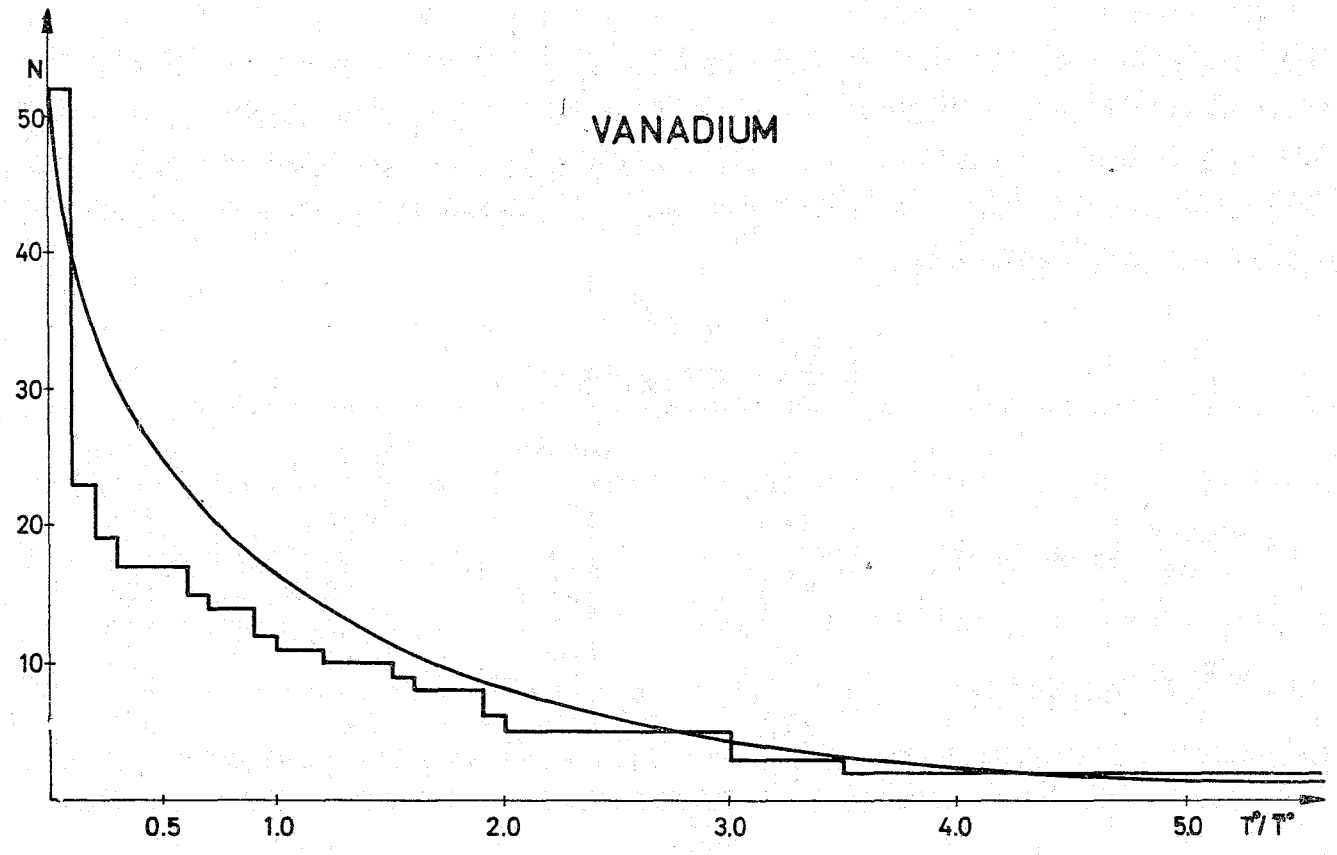

Fig. 3. Number of levels N with a normalized reduced width larger than $\Gamma_n^0/\bar{\Gamma}_n^0$ for ^{51}V. The smooth curve shows the Porter-Thomas distribution.

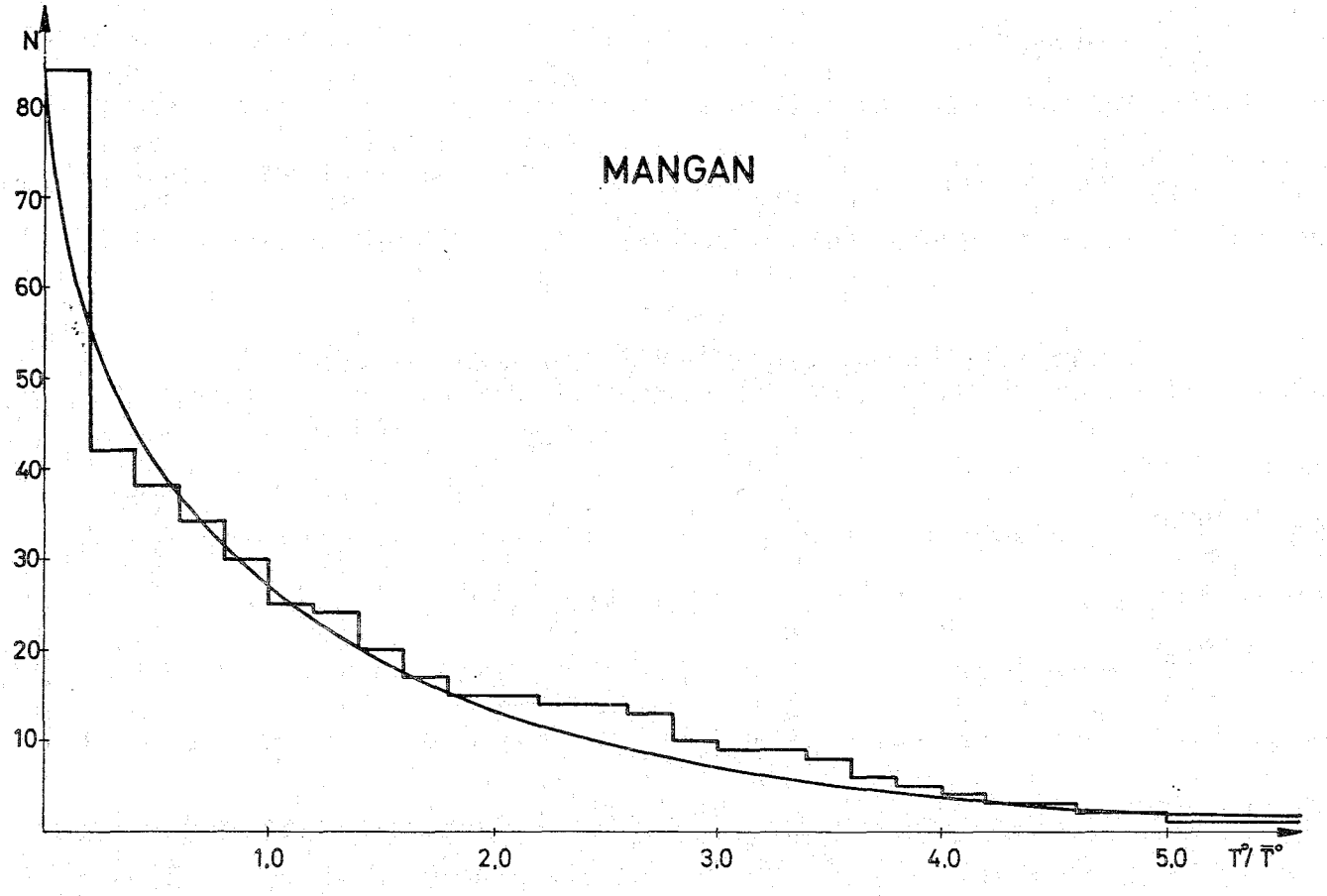

Fig. 4. Number of levels N with a normalized reduced width larger than $\Gamma_n^0/\bar{\Gamma}_n^0$ for ^{55}Mn. The smooth curve shows the Porter-Thomas distribution.

been detected experimentally. It is difficult to believe that p-waves are responsible for these additional peaks, and it must consequently be concluded that the assumption of a Porter-Thomas distribution is not valid in this particular nucleus. For a study of the width distribution, therefore, instead of using the missed level theory, all detectable but not analysed peaks were taken into account. Their widths were taken to be below one tenth of the average level width. Fig. 3 shows the resulting distribution independent of the spin. In this representation, N is the number of levels with a normalized reduced width larger than $\Gamma_n^0/\bar{\Gamma}_n^0$. The experimental result is given as a histogram with a smooth curve representing the Porter-Thomas distribution. As can be seen from the graph, the agreement is poor; a definite shortage of levels with medium widths is observed.

For manganese, the missed level theory predicts 42 resonances below the resolution limit. At least 11 of them can be distinguished from the cross-section curve. The rest might be responsible for the few regions where the calculated cross section is lower than the observed results. The reduced width of these small levels can again safely be taken as one tenth of the average value. The resulting distribution is given in fig. 4. Here the two spin systems were treated separately and added afterwards to get better statistics. As expected with the above assumption, an agreement with the Porter-Thomas distribution is found. The agreement is equally good if the spin-independent distribution is used.

The different behaviour of the width distributions for ^{51}V and ^{55}Mn might perhaps be explained by shell effects. In vanadium, the $f_{\frac{7}{2}}$ neutron shell is closed. A nucleon interacting only with the neutrons of the nucleus will, at excitation energies of less than 10 MeV form very simple excited states due to the low level density above the ground state. Most probably only two-particle–one-hole states, which are known as doorway states, will be created, leading to very broad resonances when decaying into the open channel [6]). If, however, the excitation energy is taken partly or wholly by the protons of the nucleus, the situation is quite different. Due to the partly filled $f_{\frac{7}{2}}$-proton shell, a large level density is now available, enabling the nucleus to form more complicated compound states which have, as a consequence of the two-particle character of nuclear forces, a much longer lifetime. One expects, therefore, in the spectrum a superposition of two systems with widely differing average widths. It cannot be expected that such a combination will obey a Porter-Thomas distribution.

In the case of manganese, the proton and neutron shells are both not closed, and a more uniform distribution is the result.

4.3. STRENGTH FUNCTIONS

The strength function of vanadium has been determined before only from averaged cross sections. In a paper of Buck and Perey [7]), a value of $10.4 \cdot 10^{-4}$ measured by a group from Duke University, is given. In a later publication, Seth *et al.* [8]) found a value of $(4.2 \pm 1.0) \cdot 10^{-4}$, showing the difficulty of calculating strength function from averaged cross sections in this case.

For manganese our results agree with those of other workers [3, 8]).

We expect that our experimental results for S given in tables 5 and 6 are correct within 8 %. After the correction for missed resonances these functions are:

$$(S)_0^{160} = (8.1 \pm 0.7) \times 10^{-4} \text{ for } {}^{51}\text{V},$$
$$(S)_{50}^{210} = (3.3 \pm 0.3) \times 10^{-4} \text{ for } {}^{55}\text{Mn}.$$

The indices outside the square brackets indicate the energy intervals considered for the determination of the strength function.

The reliability of the above values as representative of the energy independent strength function of these nuclei depends on the number of levels in the analysed energy range and on whether this range is large enough to render the average insensitive to intermediate structure. If the latter is assumed, the most probable strength-function and the expected statistical error can be estimated by a method given by Muradyan and Adamschuk [9]). Applying this method, we get for the strength functions

$$S = (8.2^{+2.2}_{-1.9}) \times 10^{-4} \text{ for } {}^{51}\text{V},$$
$$S = (3.1^{+0.9}_{-0.7}) \times 10^{-4} \text{ for } {}^{55}\text{Mn}.$$

Assuming a spherical symmetrical potential, the optical model predicts a maximum for the s-wave strength function near $A = 55$ and $A = 155$. The experimental results have shown quite clearly that the peak at $A = 155$ is a double peak. Such splitting was explained by Buck and Percy [7]) by collective motions. Their calculations predict also that the maximum at $A = 55$ is shifted to about $A = 50$ if the nuclei are assumed to be dynamically deformable in this mass region. Experimental results are at present not good enough to distinguish between these two models. From our results, however, it seems that the maximum of the s-wave strength function is nearer to $A = 50$ than $A = 55$, which would support the results of Buck and Perey also for medium-mass nuclei.

The spin dependence of the strength function is one of the questions which is currently receiving increasing attention. A $(2J+1)$-dependence is proposed by some workers. Some of the results of Julien *et al.* [10]) on spin $\frac{3}{2}$ nuclei seem to support this, while widely varying results have been observed for nuclei with target spin $\frac{1}{2}$. Julien *et al.* measured a ratio of $S_0/S_1 = 7$ for ^{77}Se, finding the larger strength function for the smaller spin. The opposite has been found by Ribon *et al.* [11]) and Pönitz [12]) for ^{104}Rh; both find a value $S_1/S_0 > 2$. No spin dependence has been found by Chrien *et al.* [13]) for the rare earths used in their experiments.

All the above mentioned results have in common that they were determined by considering a very limited energy range only. Intermediate structure effects will probably be an important factor in those measurements, thus explaining the inconsistent results for the different nuclei.

To demonstrate this, we have listed in tables 8 and 9, the spin dependent strength

functions calculated for 50 keV intervals. Especially for vanadium, where very simple compound states (isolated doorway) are highly probable due to shell closure, strongly contradicting results are obtained for different energy intervals.

TABLE 8
Energy dependence of the strength function S_J for vanadium

E(keV)	0–50	50–100	100–160
S_3	$14.4 \cdot 10^{-4}$	$9.80 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$
S_4	$2.74 \cdot 10^{-4}$	$7.05 \cdot 10^{-4}$	$17.2 \cdot 10^{-4}$
S_4/S_3	0.2	0.7	5

TABLE 9
Energy dependence of strength function S_J for managanese

E(keV)	50–100	100–150	150–200
S_2	$1.01 \cdot 10^{-4}$	$3.96 \cdot 10^{-4}$	$2.98 \cdot 10^{-4}$
S_3	$3.48 \cdot 10^{-4}$	$3.22 \cdot 10^{-4}$	$3.05 \cdot 10^{-4}$
S_3/S_2	3.4	0.8	1.0

Our results for the total energy range measured are as follows:

vanadium	manganese
$(S_3)_{10}^{160} = (7.4 \pm 0.7) \cdot 10^{-4}$,	$(S_2)_{50}^{210} = (2.8 \pm 0.5) \cdot 10^{-4}$
$(S_4)_{10}^{160} = (8.3 \pm 0.7) \cdot 10^{-4}$	$(S_3)_{50}^{210} = (3.8 \pm 0.5) \cdot 10^{-4}$.

Applying again the method of Muradyan and Adamschuk, we find the energy independent values

vanadium	manganese
$S_3 = (6.8^{+3.6}_{-2.1}) \cdot 10^{-4}$,	$S_2 = (2.8^{+1.3}_{-0.9}) \cdot 10^{-4}$,
$S_4 = (7.7^{+3.6}_{-2.2}) \cdot 10^{-4}$,	$S_3 = (3.9^{+1.7}_{-1.2}) \cdot 10^{-4}$.

We therefore get no spin dependence for both nuclei within the statistical uncertainty. Unfortunately, the statistical error in the above values is so large that a $(2J+1)$ dependence cannot be excluded either. To answer this question it is necessary to study target nuclei with spin $\frac{1}{2}$ where the difference would be more prominent.

With present spectrometer resolutions, it can be hoped only near the 3s-maximum of the strength function to find a sufficient number of resonances over an energy range large compared with the intermediate structure. Unfortunately in this mass region, pure separated isotopes have to be used. Such measurements are now in progress in this laboratory.

4.4. SPIN DEPENDENCE OF THE LEVEL DENSITY

Enough resonances for manganese have been measured to determine the spin cut-off parameter from the Bethe formula [14]), for the compound nucleus ^{56}Mn.

A value of $\sigma = 3.3^{+1.7}_{-0.8}$ is found without missing levels. Correcting for them this value changes to

$$\sigma = 2.5^{+0.7}_{-0.3}.$$

The stated errors are the statistical uncertainties as expected from the Wigner distribution of the level distances. The spin cut-off parameter for ^{56}Mn has been given by Ericson [15]) as 4.5. It was calculated by making use of the total level density as found from (d, p) reactions by Green *et al.* [16]) and the neutron scattering results of Marshak and Newson [17]). In this case, the combined level density at the neutron binding energy for the two possible spin systems was calculated from only six resonances. Substituting our results for those from ref. [17]), the same calculation is found to yield $\sigma = 3.4$ if not corrected for missed levels, and $\sigma = 2.7$ when this correction is applied. One can see that the values for both methods are in good agreement.

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