NRL Report 6783

An Empirical Approach to Thermal Neutron Absorption Cross Sections

S. Podgor

Theory Branch
Nuclear Physics Division

September 26, 1968

NAVAL RESEARCH LABORATORY
Washington, D.C.

This document has been approved for public release and sale; its distribution is unlimited.

ABSTRACT

A simple procedure is proposed to simulate the cyclic variation of the thermal neutron absorption cross sections of the odd-Z, even-N nuclei. The assumption is made that the cross sections vary with (a) the number of protons in the last open proton shell, and (b) the number of neutron holes in the last open neutron shell. With the major nuclear shells as a basis and with variations as to which subshells are included, empirical results are obtained and compared with the experimental cross-section curve. Preliminary indications are that the proposed method gives results that follow the trend of the experimental data.

PROBLEM STATUS

This is a final report on one phase of the problem.

AUTHORIZATION

NRL Problem H01-06
Project RR 002-06-41-5003

Manuscript submitted August 1, 1968.

AN EMPIRICAL APPROACH TO THERMAL NEUTRON ABSORPTION CROSS SECTIONS

INTRODUCTION

A problem of continuing interest in nuclear physics is the relation of nuclear properties to nuclear composition. Among these porperties, the thermal neutron absorption cross section is important from a basic as well as an applied viewpoint. It has been shown previously (1,2) that these cross sections depend on the pairing of the protons and neutrons of the nuclei. It has also been indicated (2) that there is a definite cyclic variation in the cross sections, particularly in the case of the odd-Z, even-N nuclei. In this report, a more detailed analysis of the cyclic variation will be attempted.

PRELIMINARY CONSIDERATIONS

Before we come to the cyclic variation, some general trends in the thermal absorption cross sections are considered. If the cross sections of all the stable nuclei are looked at from a statistical point of view, three approximate rules can be stated. The first two are as follows:

1. For two nuclei (Z_a, N_i) and (Z_a, N_j), where $N_j = N_i + 2$, the cross section of the second nucleus is usually smaller than that of the first. Some of the exceptions occur when N_i is a closed neutron shell.

2. Conversely, for two nuclei (Z_i, N_a) and (Z_j, N_a), where $Z_j = Z_i + 2$, the second nucleus usually has a higher cross section than the first. Exceptions occur when Z_j is a closed shell of protons.

The reason that these rules involve the adding of two nucleons at a time is to eliminate the odd-even effect. The third regularity is of a slightly different type.

3. If Z_s is a closed proton shell, and $Z_a = Z_s - 1$, $Z_b = Z_s + 1$, then the nucleus Z_a usually has a much higher cross section than Z_b.

These rules are based on cross-section data taken from Brookhaven National Laboratory Report 325 (3).

ANALYSIS OF CYCLIC VARIATION

An empirical procedure from which the above regularities can be derived is the following:

The absorption cross section is assumed to vary directly with (a) the number of protons in the last open proton shell and (b) the number of neutron holes in the last open neutron shell.

The method assumed here is very simple, without any normalization or variable parameters inserted.

This method has been applied to the odd-Z, even-N nuclei for Z > 20. The major nuclear shells are taken to be 20, 28, 50, 82, 126, and 184. Table 1 lists the odd-Z nuclei where P is the number of protons in the last open proton shell, H is the number of neutron holes in the last open neutron shell, PH is the product of the last two quantities, and σ_a is the experimental thermal neutron absorption cross section. If N is a closed neutron shell, H is set equal to unity. This is done to avoid predicting a zero cross section.

Table 1

A Comparison of Empirical and Experimental Thermal Absorption Cross Sections, in Which P = Number of Open Protons, H = Number of Neutron Holes, and PH is the Product. The Nuclear Shells Assumed are 20, 28, 50, 82, 126, and 184.

Nucleus	Z	N	P	H	PH	σ_a (barns)
H^{1}	1	0				0.332
Li^{7}	3	4				0.037
B^{11}	5	6				0.005
N^{15}	7	8				2.4×10^{-5}
F^{19}	9	10				0.0098
Na^{23}	11	12				0.534
Al^{27}	13	14				0.235
P^{31}	15	16				0.19
Cl^{35}	17	18				44
Cl^{37}	17	20				0.43
K^{39}	19	20				1.94
K^{41}	19	22				1.30
Sc^{45}	21	24	1	4	4	25
V^{51}	23	28	3	1*	3	4.9
Mn^{55}	25	30	5	20	100	13.3
Co^{59}	27	32	7	18	126	37.2
Cu^{63}	29	34	1	16	16	4.51
Cu^{65}	29	36	1	14	14	2.2
Ga^{69}	31	38	3	12	36	2.1
Ga^{71}	31	40	3	10	30	5.0
As^{75}	33	42	5	8	40	4.3
Br^{79}	35	44	7	6	42	10.8
Br^{81}	35	46	7	4	28	3.1
Rb^{85}	37	48	9	2	18	0.76
Rb^{87}	37	50	9	1*	9	0.12
Y^{89}	39	50	11	1*	11	1.28
Y^{91}	39	52	11	30	330	1.07
Nb^{93}	41	52	13	30	390	1.16
Tc^{99}	43	56	15	26	390	22
Rh^{103}	45	58	17	24	408	150
Ag^{107}	47	60	19	22	418	35
Ag^{109}	47	62	19	20	380	91
In^{113}	49	64	21	18	378	58
In^{115}	49	66	21	16	336	199
Sb^{121}	51	70	1	12	12	7.0
Sb^{123}	51	72	1	10	10	4.1
I^{127}	53	74	3	8	24	7.0
I^{129}	53	76	3	6	18	28
I^{131}	53	78	3	4	12	50
Cs^{133}	55	78	5	4	20	28
Cs^{135}	55	80	5	2	10	8
Cs^{137}	55	82	5	1*	5	0.11
La^{139}	57	82	7	1*	7	8.2
Pr^{141}	59	82	9	1*	9	11.2
Pr^{143}	59	84	9	42	378	89
Pm^{147}	61	86	11	40	440	200
Pm^{149}	61	88	11	38	418	1,700
Eu^{151}	63	88	13	38	494	8,800
Eu^{153}	63	90	13	36	468	390
Eu^{155}	63	92	13	34	442	14,000
Tb^{159}	65	94	15	32	480	46
Ho^{165}	67	98	17	28	476	67
Tm^{169}	69	100	19	26	494	127
Lu^{175}	71	104	21	22	462	23
Ta^{181}	73	108	23	18	414	21
Re^{185}	75	110	25	16	400	105
Re^{187}	75	112	25	14	350	73
Ir^{191}	77	114	27	12	324	924
Ir^{193}	77	116	27	10	270	112
Au^{197}	79	118	29	8	232	98.8
Au^{199}	79	120	29	6	174	30
Tl^{203}	81	122	31	4	124	11.4
Tl^{205}	81	124	31	2	62	0.80
Bi^{209}	83	126	1	1*	1	0.034
Ac^{227}	89	138	7	46	322	830
Pa^{231}	91	140	9	44	396	200
Pa^{233}	91	142	9	42	378	43
Np^{237}	93	144	11	40	440	170
Np^{239}	93	146	11	38	418	43
Am^{241}	95	146	13	38	494	630
Am^{243}	95	148	13	36	468	180
Bk^{249}	97	152	15	32	480	500
Es^{253}	99	154	17	30	510	300
Es^{255}	99	156	17	28	476	40

*To avoid predicting a zero cross section, H = 1 is used in place of H = 0.

Figure 1 is a plot of PH versus N, the number of neutrons in the nucleus. This curve can be compared with the experimental cross-section curve for the odd-Z nuclei shown in Fig. 2. The numbers near the points are the proton or Z numbers. The vertical lines are drawn at the closed neutron shell numbers.

A comparison of Figs. 1 and 2 shows that there is qualitative agreement in the shape of the two curves for the neutron regions 28 to 50 and 50 to 82. In the three major neutron regions between N = 28 and N = 126, the empirical curve follows the experimental trend best near the closing of the neutron shells. There, both the cross sections and the number of neutron holes are decreasing rapidly.

If in addition to the major shells assumed above, the 40-subshell is also included, Fig. 3 is obtained. This, in some ways, follows the experimental curve better than Fig. 1, particularly in the 50 to 82 neutron region. However, neither one of these two figures shows much structure in the 82 to 126 neutron region.

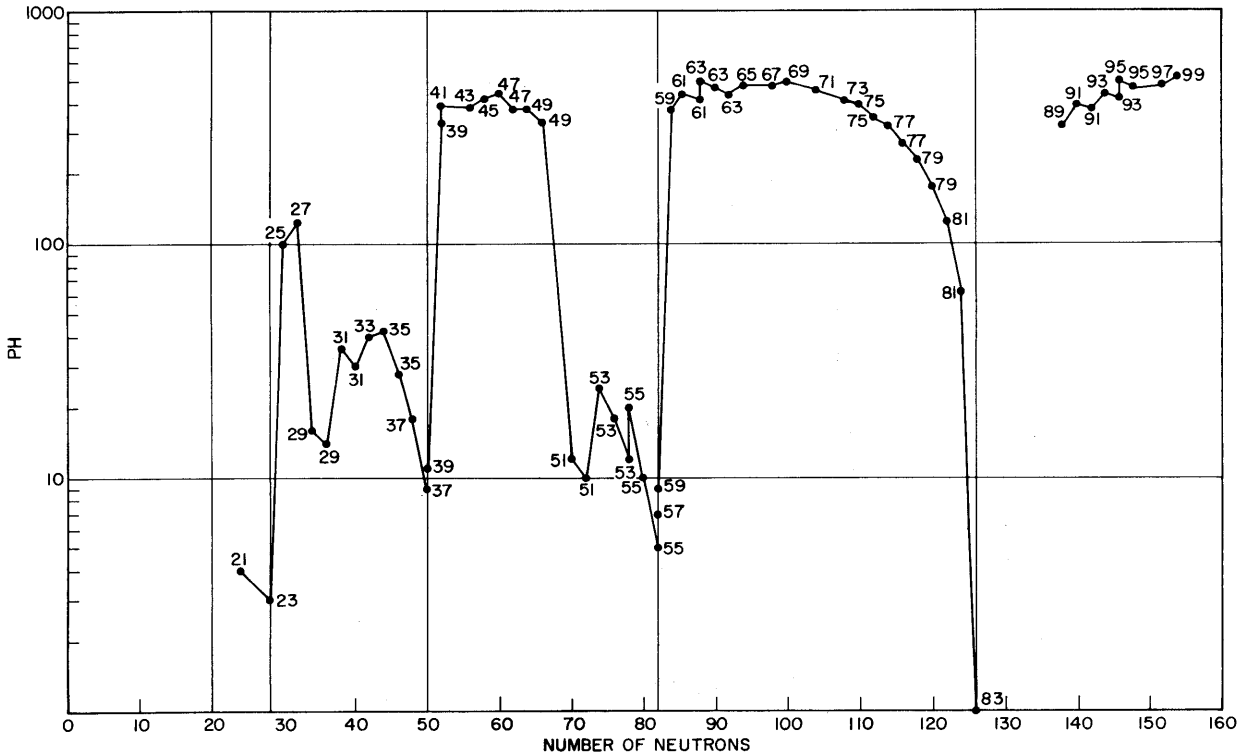

Fig. 1 - PH values from Table 1, with closed neutron and proton shells assumed for 20, 28, 50, 82, 126, and 184 nucleons. The proton or Z numbers are labeled near the points, and the closed neutron shells are indicated by vertical lines.

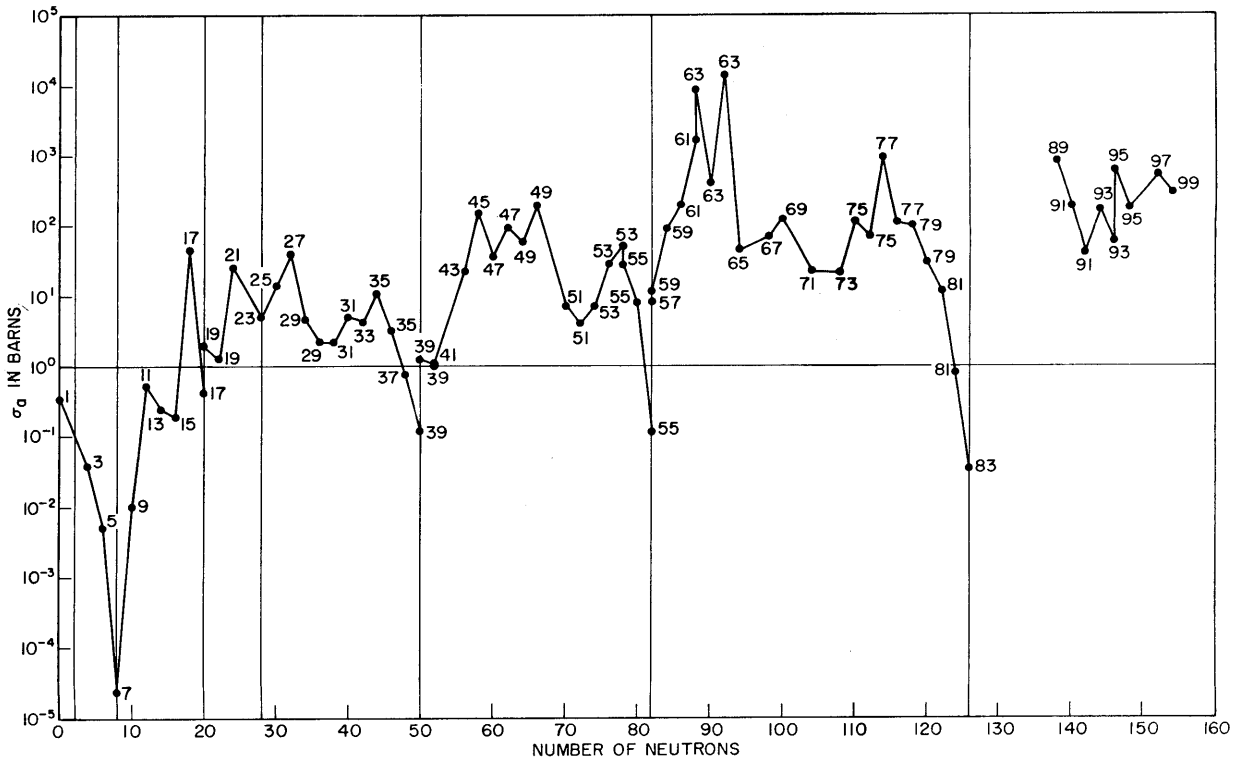

Fig. 2 - Experimental thermal neutron absorption cross sections for odd-Z, even-N nuclei

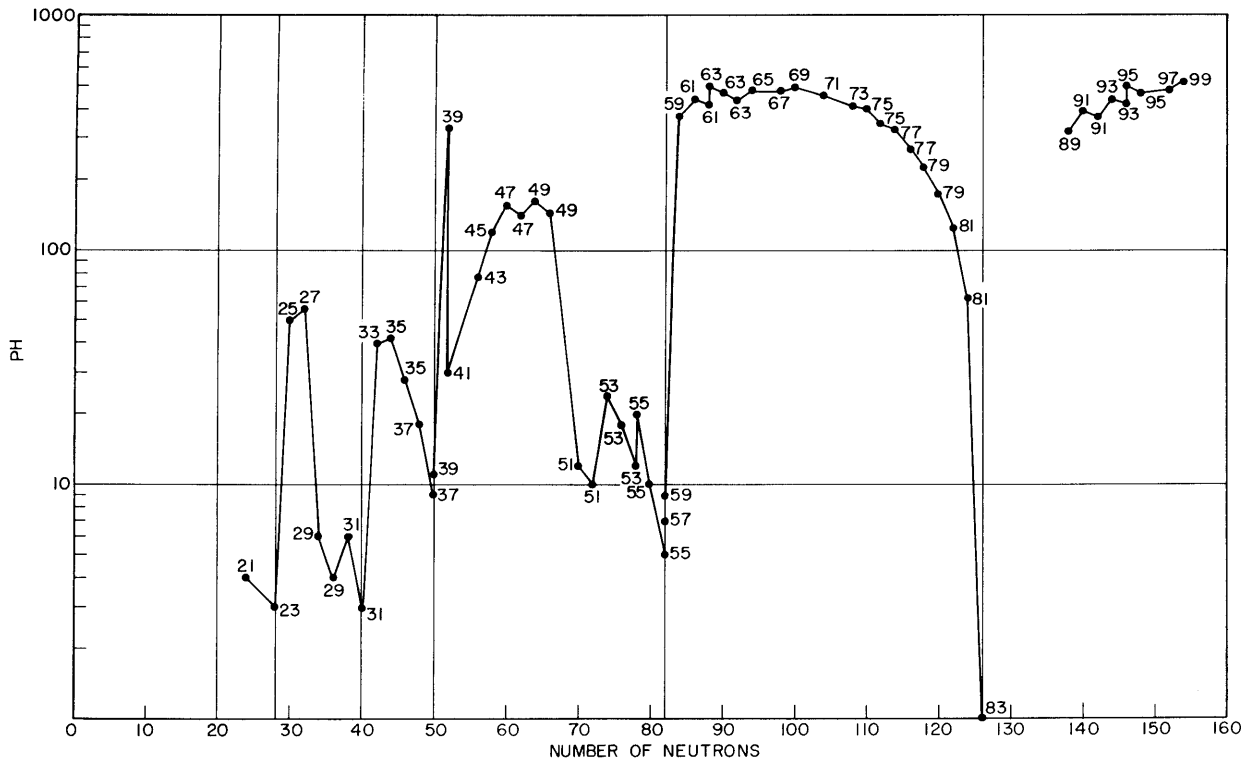

Fig. 3 - PH values obtained by including the subshell for 40 neutrons or protons as a closed shell in addition to the closed shells assumed in Table 1 and Fig. 1

If instead of the 40-subshell, the 64-subshell is included with the major shells, Fig. 4, results. Here a better qualitative match with the experimental curve is seen in the 82 to 126 region, but the 50 to 82 region does not fit the experimental curve as well as Fig. 3 does.

If the 64-subshell is replaced by the 70-subshell, Fig. 5 is the result. Again, there is a better comparison with experiment in the 82 to 126 region than in Figs. 1 and 3, but the 50 to 82 region is distorted in a somewhat different way.

One can obtain about the best overall fit to the experimental data by using, in addition to the major shells, the 40-subshell for neutrons and protons and the 70-subshell for protons only.

In the present discussion, among all the other simplifications assumed, the subshells that were used were treated on an equal basis with the major shells. Variations in this procedure could perhaps produce a better agreement with experiment. It might be well to mention that the 40- and 70-subshells are harmonic oscillator closed shells.

DISCUSSION

We have shown that with the simple procedure assumed, it has been possible to reproduce some of the features of the thermal neutron-absorption cross-section curve for odd-Z, even-N nuclei with Z > 20. The proposed method, as well as the experimental curve, gives high cross sections at the beginning of a neutron shell. Similarly they both give low cross sections at the beginning of a proton shell and higher ones toward the end

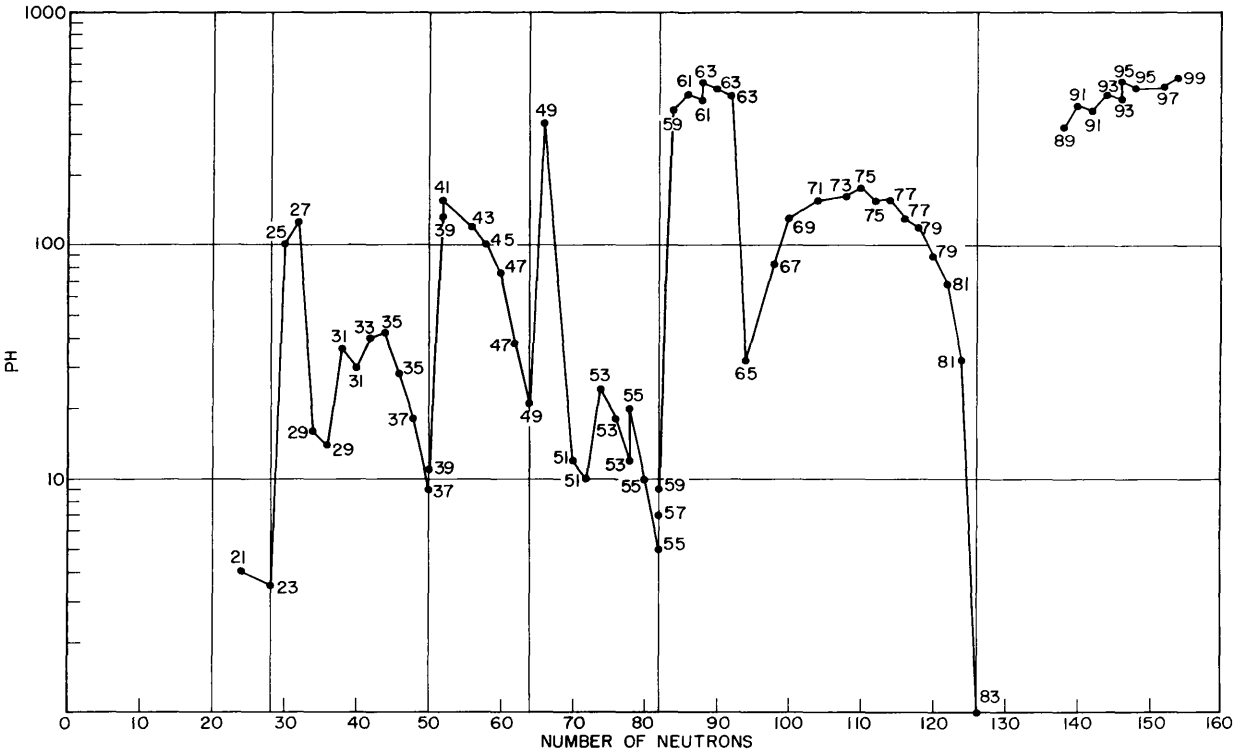

Fig. 4 - PH values obtained by including the subshell for 64 neutrons or protons as a closed shell in addition to the closed shells assumed in Table 1 and Fig. 1

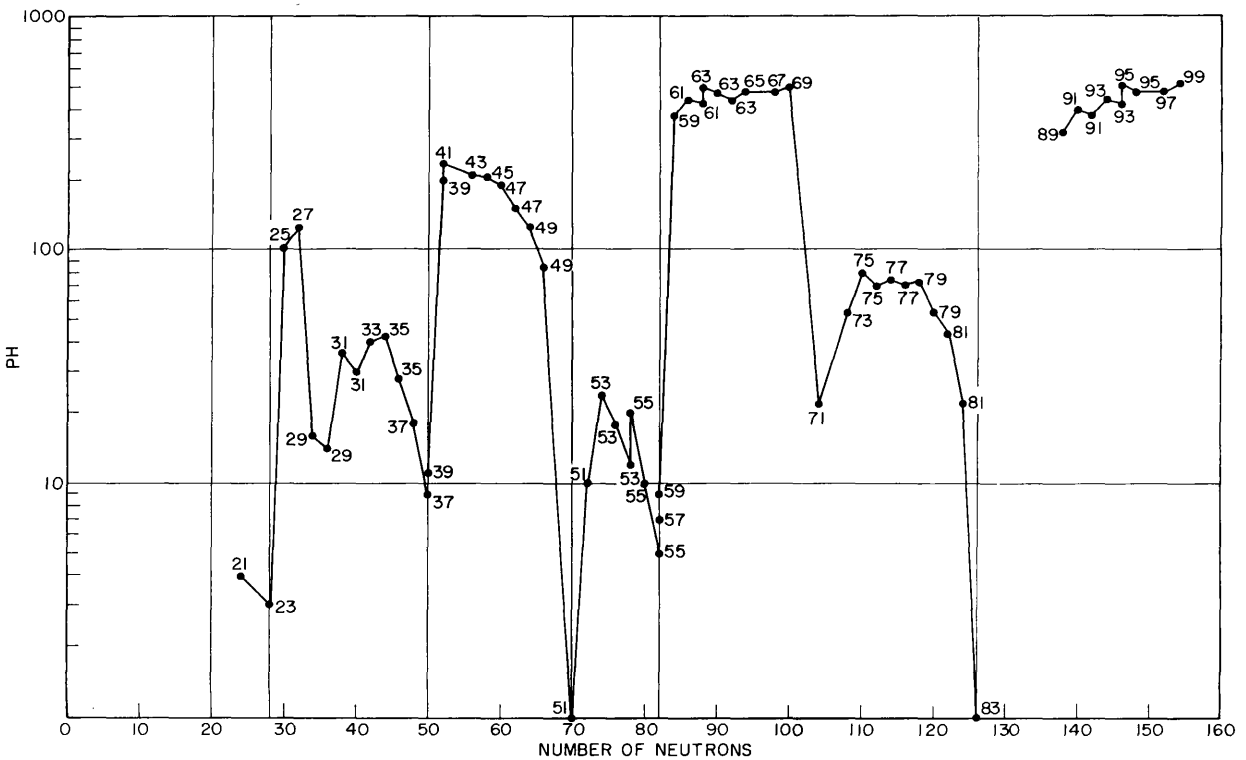

Fig. 5 - PH values obtained by including the subshell for 70 neutrons or protons as a closed shell in addition to the closed shells assumed in Table 1 and Fig. 1

of the shell. The combination of these two effects accounts for the cyclic variation of the cross-section curve. The overall trend in both the empirical and the experimental curves is an increase in the cross section with atomic weight.

The present analysis indicates that the proposed method can be developed further to obtain a better picture of the variation of neutron cross sections.

ACKNOWLEDGMENTS

The author is pleased to acknowledge informative talks with and pertinent suggestions of J. B. Aviles, Jr. He had many interesting discussions with L. A. Beach, G. H. Herling, and A. W. Sáenz.

REFERENCES

1. Hurwitz, H., Jr., and Bethe, H.A., Phys. Rev. 81:898 (1951)

2. Podgor, S., and Beach, L.A., "Regularities in Thermal Neutron Absorption Cross Section," NRL Report 6124, July 21, 1964

3. Hughes, D.J., and Schwartz, R.B., Brookhaven National Laboratory Report 325 (July 1, 1958 and all subsequent supplements)

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D. C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

AN EMPIRICAL APPROACH TO THERMAL NEUTRON ABSORPTION CROSS SECTIONS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

This is a final report on one phase of the problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

S. Podgor

6. REPORT DATE September 26, 1968	7a. TOTAL NO. OF PAGES 9	7b. NO. OF REFS 3
8a. CONTRACT OR GRANT NO. NRL Problem H01-06 b. PROJECT NO. RR 002-06-41-5003 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6783 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research) Washington, D.C. 20360

13. ABSTRACT

A simple procedure is proposed to simulate the cyclic variation of the thermal neutron absorption cross sections of the odd-Z, even-N nuclei. The assumption is made that the cross sections vary with (a) the number of protons in the last open proton shell, and (b) the number of neutron holes in the last open neutron shell. With the major nuclear shells as a basis and with variations as to which subshells are included, empirical results are obtained and compared with the experimental cross-section curve. Preliminary indications are that the proposed method gives results that follow the trend of the experimental data.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Absorption cross section Nuclear properties						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)