KERNFORSCHUNGSZENTRUM

KARLSRUHE

März 1974

KFK 2060

Institut für Angewandte Kernphysik

Optical Model Analysis of Neutron Cross Sections and Strength Functions

C.M. Newstead, S. Cierjacks

GESELLSCHAFT
FÜR
KERNFORSCHUNG M.B.H.

KARLSRUHE

GESELLSCHAFT FÜR KERNFORSCHUNG M. B. H.

KARLSRUHE

KERNFORSCHUNGSZENTRUM KARLSRUHE

March 1974 KFK 2060

Institut für Angewandte Kernphysik

Optical Model Analysis of Neutron Cross Sections and Strength Functions

C.M. Newstead
S. Cierjacks

Gesellschaft für Kernforschung mbH, Karlsruhe

Paper presented at the EANDC Topical Conference on Critique of Nuclear Models and their Validity in the Evaluation of Nuclear Data, Tokyo, March 27, 1974.

ABSTRACT

Current problems met in the attempt to interpret fast neutron total cross sections with spherical and coupled channels optical model calculations are discussed. The energy dependence of the real and imaginary potential strengths is considered and progress in fitting neutron total cross sections over a wide energy range is discussed. Fluctuations in the strength of the imaginary potential are investigated in terms of the s-and p-wave neutron strength function. The role of strength function systematics in aiding study of the optical potential is developed. The implications, of energy and mass dependences of the optical potential for neutron data predictions are outlined.

ZUSAMMENFASSUNG

Die derzeitige Problematik im Zusammenhang mit der Interpretation von Neutronenquerschnitten mit Hilfe des optischen Modells wird diskutiert. Dabei werden sowohl die Ergebnisse für ein nichtlokales, kugelsymmetrisches Potential, als auch die Vorhersagen von coupled-channel Rechnungen betrachtet. Die zur Interpretation der Daten angenommene Energieabhängigkeit der Potentialtopftiefen für den Real- und den Imaginärteil wird untersucht. Die in letzter Zeit bezüglich der Interpretation der experimentellen Daten erzielten Fortschritte werden in zusammengefaßter Form wiedergegeben. Unter Zuhilfenahme der neueren Werte für die s- und p-Wellen-Stärkefunktionen folgt eine Studie über mögliche Fluktuationen in der Massenabhängigkeit für den Imaginärteil des Potentials. Es wird die besondere Bedeutung aufgezeigt, welche den systematischen Untersuchungen von Stärkefunktionen in Hinblick auf die Auswahl geeigneter Potentialansätze zukommt. Der Bericht schließt mit einer Bewertung der derzeitigen Vorhersagemöglichkeiten von mittleren Neutronenquerschnitten ab.

OPTICAL MODEL ANALYSIS OF NEUTRON CROSS SECTIONS AND STRENGTH FUNCTIONS

C.M. Newstead
Physics Department, Combustion Engineering, Inc.
Windsor, Connecticut

and

Institut für Angewandte Kernphysik
Kernforschungszentrum Karlsruhe

and

S. Cierjacks
Institut für Angewandte Kernphysik
Kernforschungszentrum Karlsruhe

ABSTRACT

Current problems met in the attempt to interpret fast neutron total cross sections with spherical and coupled channels optical model calculations are discussed. The energy dependence of the real and imaginary potential strengths is considered and progress in fitting neutron total cross sections over a wide energy range is discussed. Fluctuations in the strength of the imaginary potential are investigated in terms of the s-and p-wave neutron strength function. The role of strength function systematics in aiding study of the optical potential is developed. The implications of energy and mass dependences of the optical potential for neutron data predictions are outlined.

INTRODUCTION

The optical model has been remarkably successful in describing a variety of nuclear reactions encompassing a wide energy range. In recent years a number of global potentials have been proposed each of which has particular merits in describing the gross features of particular sets of reactions. To assess the validity of the several forms of the optical model and the various potentials for the actual evaluation of nuclear data one is concerned not with a global description but rather with the extent of the departure from it. By comparison of the optical model predictions with accurately measured cross sections we can hope to learn in what way and perhaps even why the potentials depart from their global trends. In an attempt to investigate these variations we have: 1) compared the predictions of the model with neutron total cross sections over a wide energy range to study the energy dependence of the optical potential strength and 2) considered the accuracy of the model in predicting s- and p-wave neutron strength functions for a number of nuclei to both obtain information concerning the strength of the potential at low energy and its variation with mass number. It is hoped that this and similar studies may serve as some guide to evaluators faced with the problem of choosing a potential suitable for a particular mass and energy range.

TOTAL CROSS SECTION ANALYSIS

Theoretically the total neutron cross section constitutes a remarkable and constantly varying mixture of elastic and inelastic partial cross sections. From an experimental standpoint the total cross section can be measured absolutely with high precision. Thus analysis of the variation of the total cross section with energy provides a useful tool for study of the optical potential.

In what follows we present the results of a series of total cross section measurements carried out at the Karlsruhe cyclotron and their analysis in terms of the spherical non-local optical model potential of Perey and Buck. We then attempt to understand the observed departures from this global description in terms of simple physical considerations.

Total neutron cross sections for a variety of spherical and vibrational nuclei ranging from calcium to bismuth were measured with a nominal resolution of 0.04 nsec/m in the energy range 0.5 to 40 MeV with the fast neutron time-of-flight spectrometer of the Karlsruhe isochronous cyclotron. For the present study these high resolution results were averaged with a sliding energy width of 500 keV. The resulting average cross sections are plotted in figure 1 and compared to the predictions of the spherical non-local optical model of Perey and Buck[1). We note that below 3 MeV and above approximately 20 MeV the agreement between theory and experiment rapidly deteriorates.

In a previous investigation carried out with moderate energy resolution in the energy range 2.5 to 15 MeV, Foster and Glasgow[2) measured the neutron total cross section of a number of nuclei ranging from hydrogen to plutonium. Comparing their data with the predictions of the spherical non-local potential of Perey and Buck they found better than 3 % agreement for the 46 spherical or vibrational nuclei included in their study as illustrated in figure 2 for the case of various $1f_{7/2}$ shell nuclei while agreement was only within 17 % for the 19 deformed nuclei considered in their study as illustrated in figure 3 for various $1h_{9/2}$ and $2f_{7/2}$ shell nuclei.

This latter result is clearly to be expected and serves to illustrate the utility of coupled channels calculations for rotational nuclei. The former result was considered an additional triumph for the Perey-Buck model. It certainly must be regarded as an achievement since the potential was originally derived from fitting only the elastic angular distribution for 7 and 14.5 MeV neutrons on lead although the resulting potential was then compared to angular distributions and reaction cross sections for a number of nuclei at 4.1, 7- 14.5 and 24 MeV and found to give an adequate description. The remarkable success of this simple potential is most probably due to its non-locality or put another way to the fact that the local representation has a built-in energy dependence.

The present study demonstrates that the Perey-Buck potential is inadequate to describe the upper and lower regions of the extended energy range. We note that above 20 MeV an increase in the strength of the imaginary potential would yield better agreement. While this is partly a matter of energy dependence of the surface peaked absorption it is primarily due to the onset of volume absorption. The Perey-Buck potential does not include a volume absorption term. While this is perfectly justified at the energies considered in their analysis because of the inhibiting effects of the Pauli principle which dictates surface absorption at low energy, it becomes increasingly inadequate at the higher energies considered here. Of course we cannot uniquely determine the ratio of surface to volume absorption and its variation with energy from our total cross section analysis but rather can only infer the need to increase the strength of the imaginary term.

It would appear that agreement between prediction and measurement could be obtained below 3 MeV by reducing the strength of the surface peaked absorption. This is reasonably theoretically since there are less channels available for excitation at low energy.Thus in the simplest possible terms the imaginary potential may be thought of as being given by the product of an average interaction matrix element and the density of states available for interaction. When this density is low so is the imaginary potential strength.

Recently evidence for the reduction of the imaginary potential strength at low neutron energy has been forthcoming from several different sources. In the latter part of this paper evidence from neutron strength function analysis will be given. Evidence is also available from analysis of both neutron scattering and the (p,n) interaction on lead.

Fu and Perey$^{3)}$ have carried out an extensive analysis of elastic and inelastic reactions for the lead isotopes. They find it necessary to reduce the strength of the surface peaked absorption at low energy to correctly describe inelastic scattering while preserving agreement for elastic scattering. Fu and Perey employ the strengths $V = 47.0 - 0.25\ E_n$ MeV and $W = 3.5 + 0.43\ E_n$ eV. This is to be compared with the equivalent local representation of the non-local potential of Perey-Buck which has been determined by Hodgson and Wilmore$^{4)}$ to be given by $W = 47.01 - 0.267\ E_n - 0.00118\ E_n^2$ MeV and $W = 9.52 - 0.053\ E_n$ MeV. We note that these two parameterizations of the energy dependence agree well in the vicinity of 14 MeV where the Perey-Buck analysis was predominately biased by the experimental results.

Smith and co-workers[5)] have found both positive and negative energy dependent coefficients for the imaginary strength depending on the nuclei being analyzed. This may in part be due to compensation for the use of the spherical model to describe deformed or highly vibrational nuclei.

Additional evidence for the reduction of imaginary strength at low energy comes from the study of the total proton decay of isobaric analogue states near threshold. Hoffmann and Coker[6)] have suggested that the sharp drop in the (p,n) $\tilde{p}$ excitation function near threshold can be described by such a reduction. It should be noted, however, that there are a number of difficulties in both the measurement and interpretation of these excitation functions.

The energy dependence of the central or isospin independent optical potential (V_o and W_o) is intimately connected with the energy dependence of the isospin dependent optical potential or so-called Lane potential (V_1 and W_1). The energy dependence of the complex Lane potential as obtained from analysis of (n,n), (p,p), and (p,n) reactions from a few MeV up to 100 MeV has been previously discussed[7)]. This analysis tends to support Rook's[8)] theoretical calculations for the energy dependence of V_o and V_1 carried out using the Bruckner - Bethe G-matrix and the reference spectrum method of Bethe.

Isospin effects may be of importance when the optical potential is used to evaluate cross sections for chains of isotopes. Perhaps the best way to determine the strength and energy dependence of the complex Lane potential is the comparison of proton and neutron scattering at a number of different energies. The role of isospin in increasing absorption for protons as a function of increasing asymmetry (and decreasing it in the same manner for neutrons) is illustrated in figure 4 and provides the signature of the isospin component.

Unfortunately neutron angular distributions of quality comparable with their proton counterparts are not generally available because of the experimental difficulties involved in such measurements. To further our study of isospin strengths a series of high resolution differential excitation functions at ten different angles are currently planned for measurement at the Karlsruhe cyclotron to complement the total cross section work. It is recognized that the study of chains of separated isotopes will be of particular value here.

STRENGTH FUNCTION ANALYSIS

Nuclear data requirements for reactors tend to be concerned with the lower neutron energy region (if one excludes fusion and material damage requirements) while our knowledge of the optical potential tends to be based on measurements and calculations carried out in large measure at higher energies. In this respect study of neutron strength function systematics are particularly valuable since the strength function is intimately related to the strength of the optical potential at low energy. Since the strength function is measured for particular waves one also is spared some of the ambiguity inherent in averaging over many partial waves as is necessary at higher energies.

In recent years improvements in time-of-flight spectrometry and strength function analysis techniques have greatly increased our knowledge of accurate strength function values. In particular use of cyclotron based high resolution fast neutron spectrometers has permitted us to obtain strength functions for light nuclei and higher partial waves9) while the employment of the"sharp spike capture technique" by Block and co-workers at RPI10) has led to the measurement of strength functions in deep minima. In addition the average analysis technique as developed at Harwell11) and Saclay12) has led to the accurate determination of s-, p- and d-wave strength functions by the sampling of a large number of resonances and elimination of the necessity of individual resonance parity assignment.

Analysis of these new results by coupled channel optical model calculations has led to several interesting conclusions. It has been found that the deep s- and p-wave strength function minima can be simultaneously described by the same optical potential13). The results of the calculation are given in table 1 and figure 5 where comparison is made with the experimental values. The important point here is that the strength of the surface peaked absorption must be reduced in comparison to the value normally employed for higher energy scattering. It will be recognized that this tends to substantiate the conclusion reached in the total cross section discussion given above. It is interesting in this respect to compare the strength function predictions of the Perey-Buck spherical non-local potential with strength function measurements. This comparison is given in figure 6. We note that the Perey-Buck predictions tend to be larger than the measured values in the minima and smaller than experiments in the maxima. This is consistent with our supposition that the Perey-Buck imaginary strength (W = 9.5MeV) is too strong for the low energy region. (Note that in the maxima reduction of W results in increase of S_o.) We note that the imaginary strengths given in table 1 are considerably less than 9.5 MeV.

Sometime ago Moldauer[14)] proposed an optical potential which gave good agreement with the s-wave neutron strength functions for the mass 100 region and also provided a good description of neutron scattering near 1 MeV. In a series of investigations Smith and co-workers[5)] have verified the utility of the Moldauer potential for the description of low energy neutron interactions. The essential characteristics of the Moldauer potential are the reduction in width of the surface peaked absorption and the translation of the location of the absorptive band by a small amount outside the nuclear half-way radius. One can regard this as a way of reducing the imaginary potential strength rather than having any deeper physical significance associated with diffuseness or polarization of the nuclear matter distributions. Such an interpretation would be consistent with the interpretation of our study. It should be mentioned that the RPI group has proposed an explanation of the deep strength function minima based upon the optical potential being different for s- and p-waves. While this is acceptable theoretically it would not appear to substantiate the trend found in the total cross section analysis.

It does seem that particularly at low energy (because of the availability of states argument) the optical potential fluctuates with mass number as can be seen from table 1. In extensive scattering studies carried out at 8 MeV Holmqvist and Wiedling 15) have also found fluctuations in the strength of the potential as illustrated in figure 7.

Thus it is clear that evaluators must give some thought to the variation of the strength of the potential when attempting to make accurate assessments of neutron cross sections. Clearly at the lower energies involved in most nuclear data evaluations nuclear structure effects play an important role in modulating the global optical potential.

REFERENCES

1/ F. G. Perey, B. Buck; Nucl. Phys. 32 (1962) 353

2/ D. Foster, D. Glasgow; Phys. Rev. C3 (1971) 576
and D. Glasgow, D. Foster; Phys. Rev. C3 (1971) 604

3/ C. Y. Fu, F. G. Perey; Report, ORNL-4765 (1972)

4/ D. Wilmore, P. E. Hodgson; Nucl. Phys. 55 (1964) 673

5/ A. B. Smith, in"New Developments in Reactor Physics and Shielding" CONF-720 901, Vol. 2(1972) p. 1063 and references therein.

6/ G. W. Hoffmann, W. R. Coker; Phys. Rev. Lett. 29 (1973) 227

7/ C. M. Newstead; Bull. Am. Phys. Soc. 18 (1973) 547
and Proc. Int. Conf. on Nuclear Physics, Munich, North Holland Publishing Company, Vol. 1 (1973), p. 366

8/ H. R. Kidwai, J. R. Rook; Nucl. Phys. A169 (1971) 417,
and J. R. Rook; Nucl. Phys. to be published

9/ S. Cierjacks; Proc. II. All-Union Conf. on Neutron Physics, Kiev, Vol. 2, (1973), p. 307 and references therein.

10/ R. G. Stieglitz, R. W. Hockenbury, R. C. Block; Nucl. Phys. A163 (1971) 592 and references therein.

11/ C. A. Uttley, C. M. Newstead, K. Diment; in "Nuclear Data for Reactors", IAEA Vienna, Vol. 1 (1966) 165

12/ C. M. Newstead, J. Delaroche, B. Cauvin; in "Statistical Properties of Nuclei", Plenum Press, New York (1972), p. 367

13/ C. M. Newstead; Europhysics Study Conf. on Intermediate Processes in Nuclear Reactions, Plitvice (1973)

14/ P. A. Moldauer; Nucl. Phys. 47 (1963) 65

15/ B. Holmqvist, T. Wiedling; in "Nuclear Data for Reactors", IAEA Vienna, Vol. 2 (1970) 341

FIGURE CAPTIONS

Fig. 1 Karlsruhe neutron total cross sections versus energy for nuclei ranging from ^{40}Ca to ^{209}Bi compared to predictions of Perey-Buck spherical non-local optical model.

Fig. 2 Battelle neutron total cross sections versus energy for various $1f_{7/2}$ nuclei (with the exception of ^{44}Ca) compared to predictions of Perey-Buck spherical non-local optical model$^{2)}$.

Fig. 3 Battelle neutron total cross sections versus energy for various $1h_{9/2}$ and $2f_{7/2}$ nuclei compared to predictions of Perey-Buck spherical non-local optical model$^{2)}$.

Fig. 4 Contrast between neutron and proton imaginary potentials versus asymmetry e when the optical potential has an isospin dependent strength W_1. A similar effect occurs for the isospin dependent real potential.

Fig. 5 Comparison between experimental and theoretical values of the s- and p-wave neutron strength functions versus mass number. The solid curves are the Buck and Perey collective model predictions while the symbols + indicate the coupled channels calculations of the present study whose parameters are given in table 1.

Fig. 6 S-wave neutron strength functions predicted by the Perey-Buck spherical non-local optical model compared to experimental values. This comparison suggests that the Perey-Buck imaginary potential strength should be reduced at low neutron energy. It is understood that the spherical model is inadequate to describe the splitting of the 4 S size resonance.$^{1)}$

Fig. 7 Optical model parameters (strength and geometry) versus mass number as obtained from a study of 8 MeV neutron elastic scattering. The open circles are the result of a five parameter analysis. The solid circles are the result of a two parameter (U and W) analysis with the other parameters held fixed at average values.$^{15)}$

Table 1 Comparison of theoretical and experimental results for the s- and p-Wave strength functions

TARGET	V	W	β_2	S_0^{th}	S_1^{th}	$S_0^{exp.}$	$S_1^{exp.}$
^{35}Cl	51.04	0,9	0.0	0.15	1.15	0.08 ± 0.07	1.65 ± 0.55
^{37}Cl	48.38	0.9	0.0	0.13	2.07	0.12 ± 0.09	2.87 ± 1.06
^{39}K	48.00	2.5	0.0	0.41	2.40	0.37 ± 0.23	2.71 ± 0.82
^{40}Ca	53.50	1.5	$\beta_2=0.00$ $\beta_3=0.36$	2.16	0.31	$2.56^{+1.20}_{-0.58}$	$0.25^{+0.12}_{-0.06}$
^{50}cr	51.11	1.12	0.22	1.94	0.27	2.18 ± 0.75	0.264 ± 0.152
^{52}Cr	50.40	0.8	0.17	2.06	0.15	2.10 ± 1.05	0.053 ± 0.023
^{54}Cr	49.60	0.44	0.17	0.89	0.076	1.79 ± 1.03	0.042 ± 0.024
^{89}Y	48.97	3.6	0.0	0.44	3.92	$0.39^{+0.27}_{-0.12}$	$4.4^{+2.0}_{-1.2}$
^{93}Nb	49.15	1.35	0.0	0.15	5.18	0.17 ± 0.06	5.16 ± 0.24
^{98}Mo	48.42	6.2	0.168	0.77	7.21	0.42 ± 0.25	6.8 ± 0.5
^{100}Mo	47.90	4.0	0.253	0.74	4.43	0.55 ± 0.30	$4.6^{+0.5}_{-0.4}$
^{103}RH	48.91	3.3	0.264	0.40	5.06	$0.40^{+0.05}_{-0.08}$	$5.07^{+0.53}_{-0.29}$
^{135}Ba	47.59	4.0	0.150	1.01	1.60	1.0 ± 0.3	
^{137}Ba	47.22	1.82	0.130	0.50	0.84	$0.33+0.17$	
^{139}La	47.30	2.12	0.130	0.71	0.83	$0.70^{+0.20}_{-0.14}$	$0.70^{+0.3}_{-0.2}$
^{141}Pr	47.81	4.00	0.110	1.73		$2.04^{+0.47}_{-0.35}$	
^{165}Ho	47.5	3.00	0.30	1.82	1.61	1.66 ± 0.24	1.63 ± 0.25
^{209}Bi	46.5	1.5	$\beta_2=0.00$ $\beta_3=0.20$	0.50	0.29	$0.65^{+0.39}_{-0.17}$	$0.25^{+0.09}_{-0.05}$

Geometry set for all calculations: $r_o = 1.25$ f, a = 0.65 f, b = 0.47 f. Potentials strengths in MeV. S_o and S_1 in units of 10^{-4}.

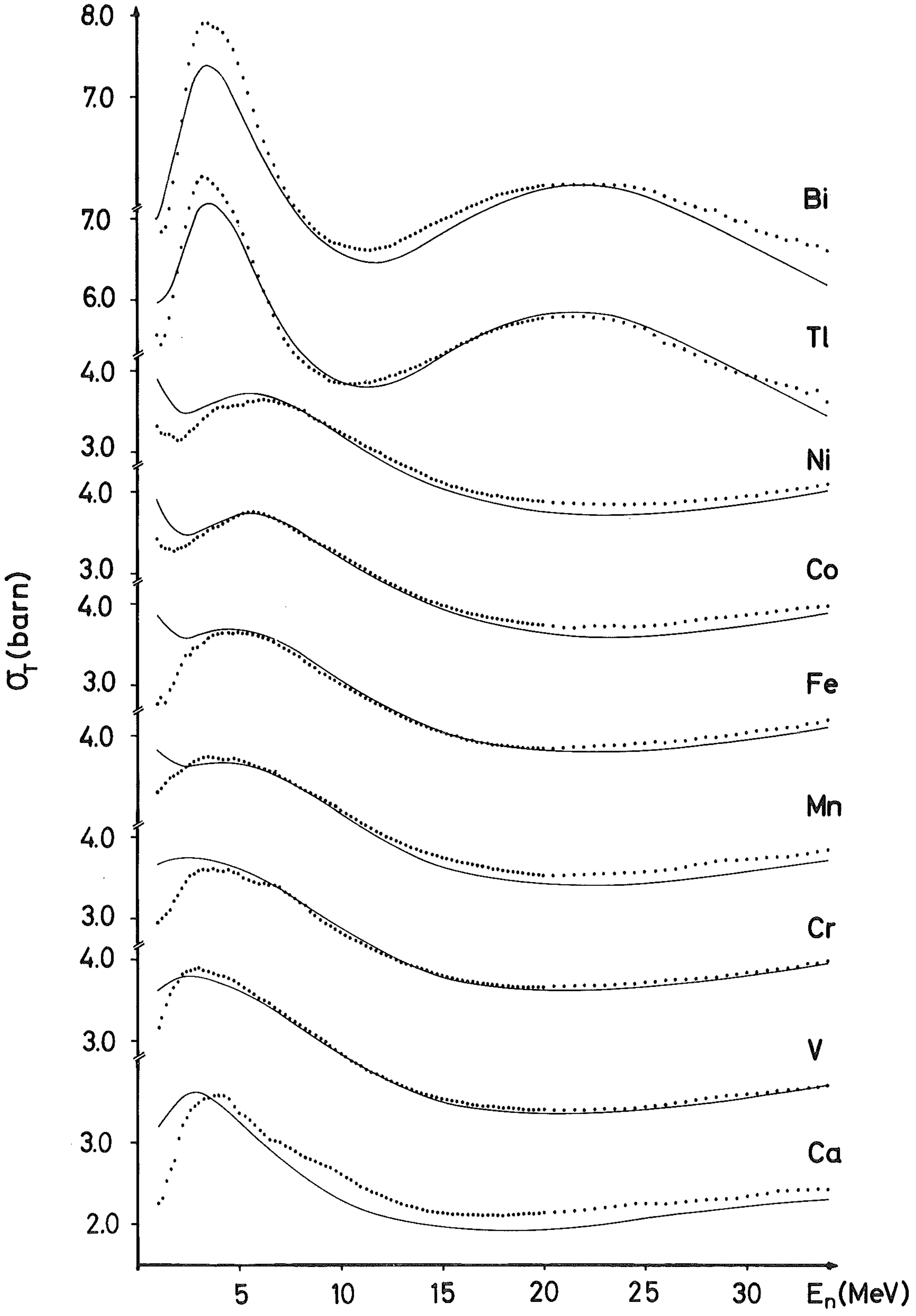
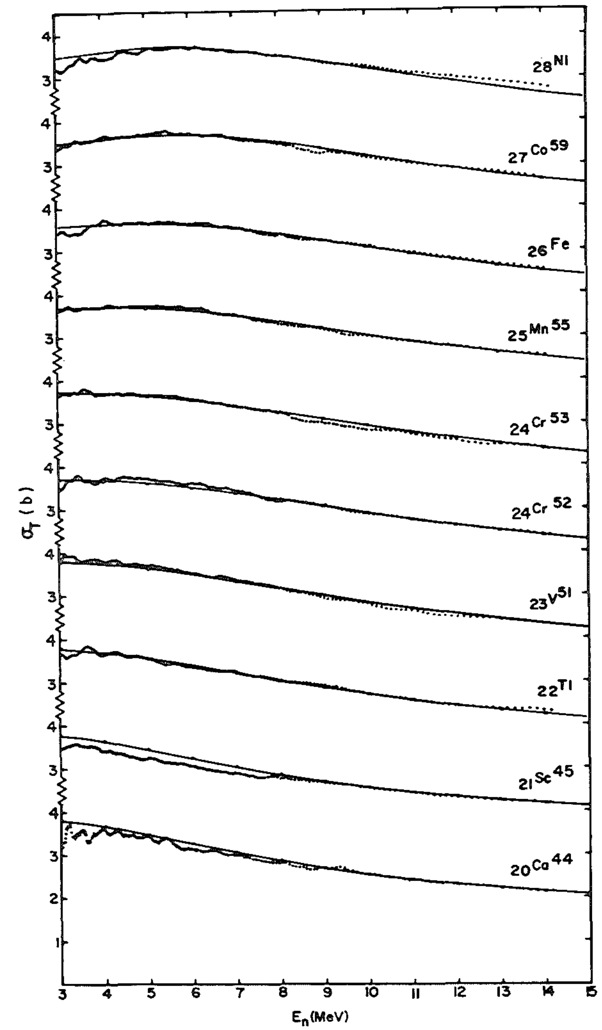
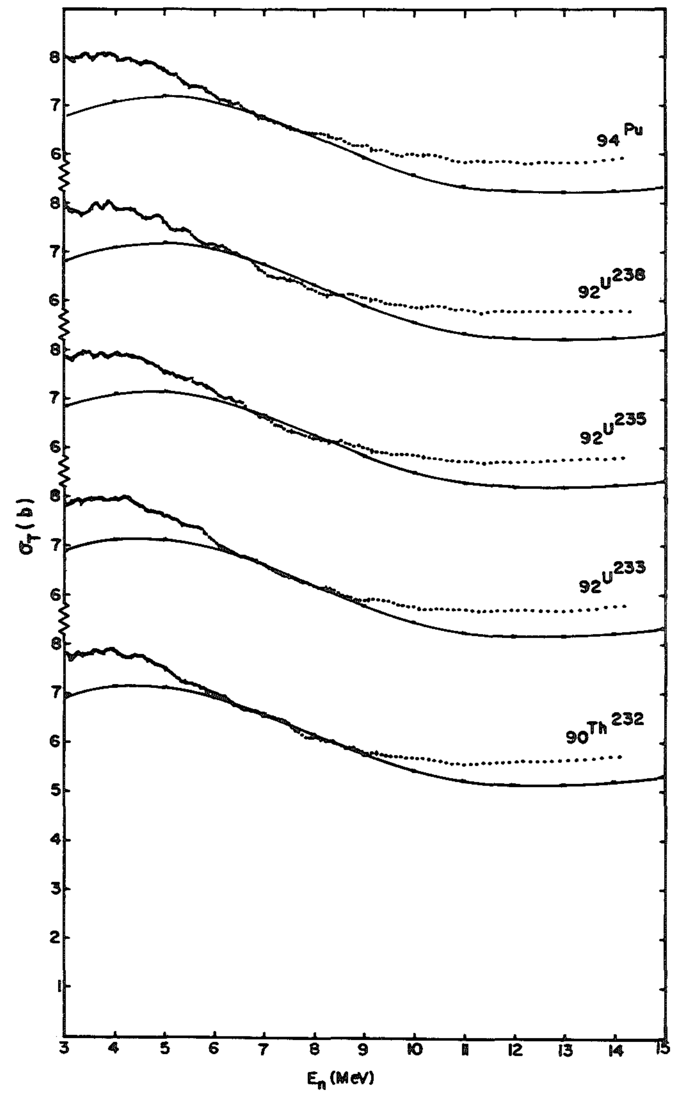

8.0
7.0
7.0
6.0
4.0
3.0
4.0
3.0
4.0
3.0
4.0
4.0
3.0
4.0
3.0
3.0
2.0
σ_T (barn)
Bi
Tl
Ni
Co
Fe
Mn
Cr
V
Ca
5
10
15
20
25
30
E_n(MeV)

Fig. 1



σ_T (b)
4
3
2
1
3
4
5
6
7
8
9
10
11
12
13
14
15
E_n(MeV)
$_{28}$Ni
$_{27}$Co^{59}
$_{26}$Fe
$_{25}$Mn^{55}
$_{24}$Cr^{53}
$_{24}$Cr^{52}
$_{23}$V^{51}
$_{22}$Ti
$_{21}$Sc^{45}
$_{20}$Ca^{44}

Fig. 2



σ_T (b)
8
7
6
5
4
3
2
1
3
4
5
6
7
8
9
10
11
12
13
14
15
E_n (MeV)
$_{94}$Pu
$_{92}$U^{238}
$_{92}$U^{235}
$_{92}$U^{233}
$_{90}$Th^{232}

Fig. 3

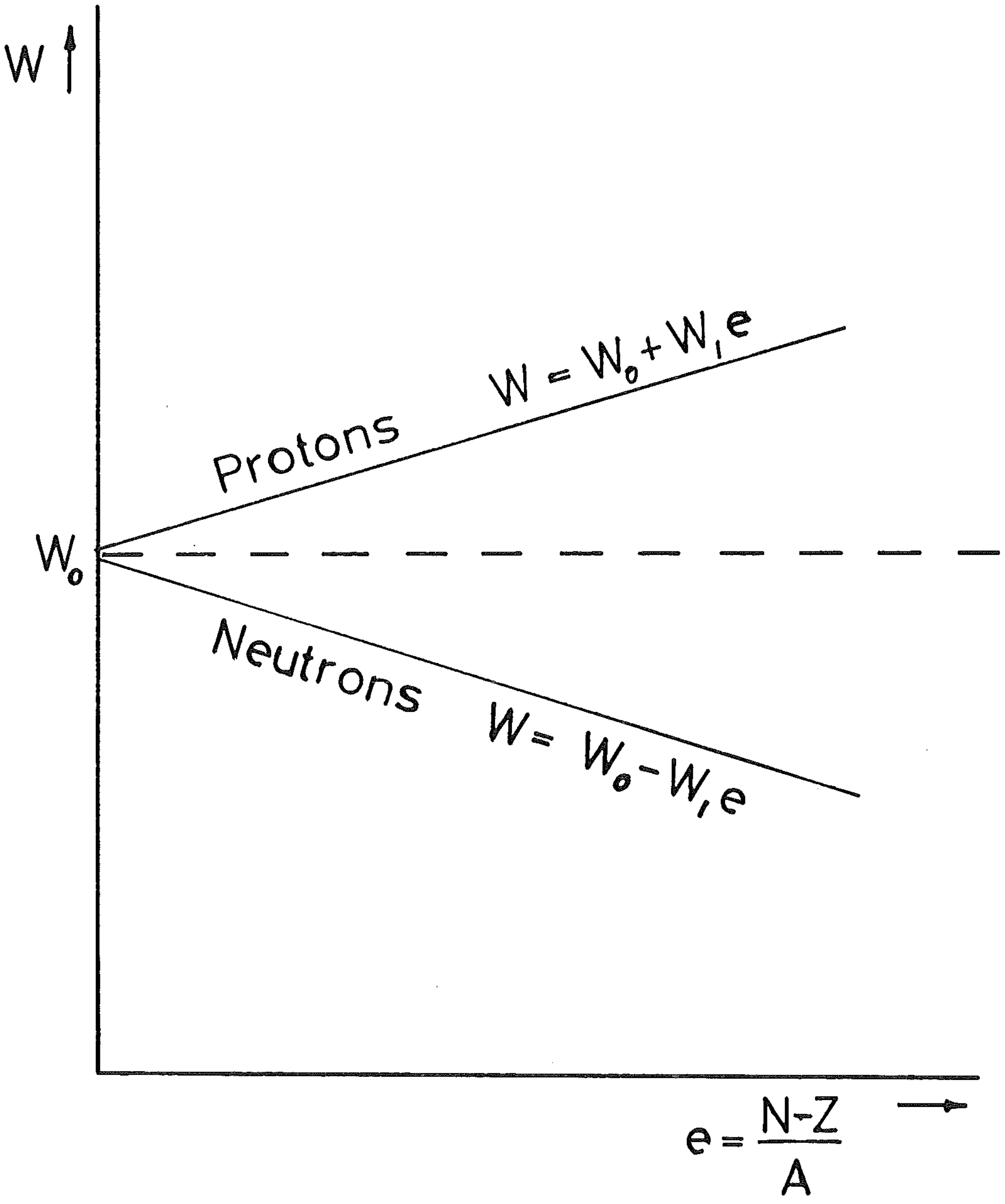


Fig. 4

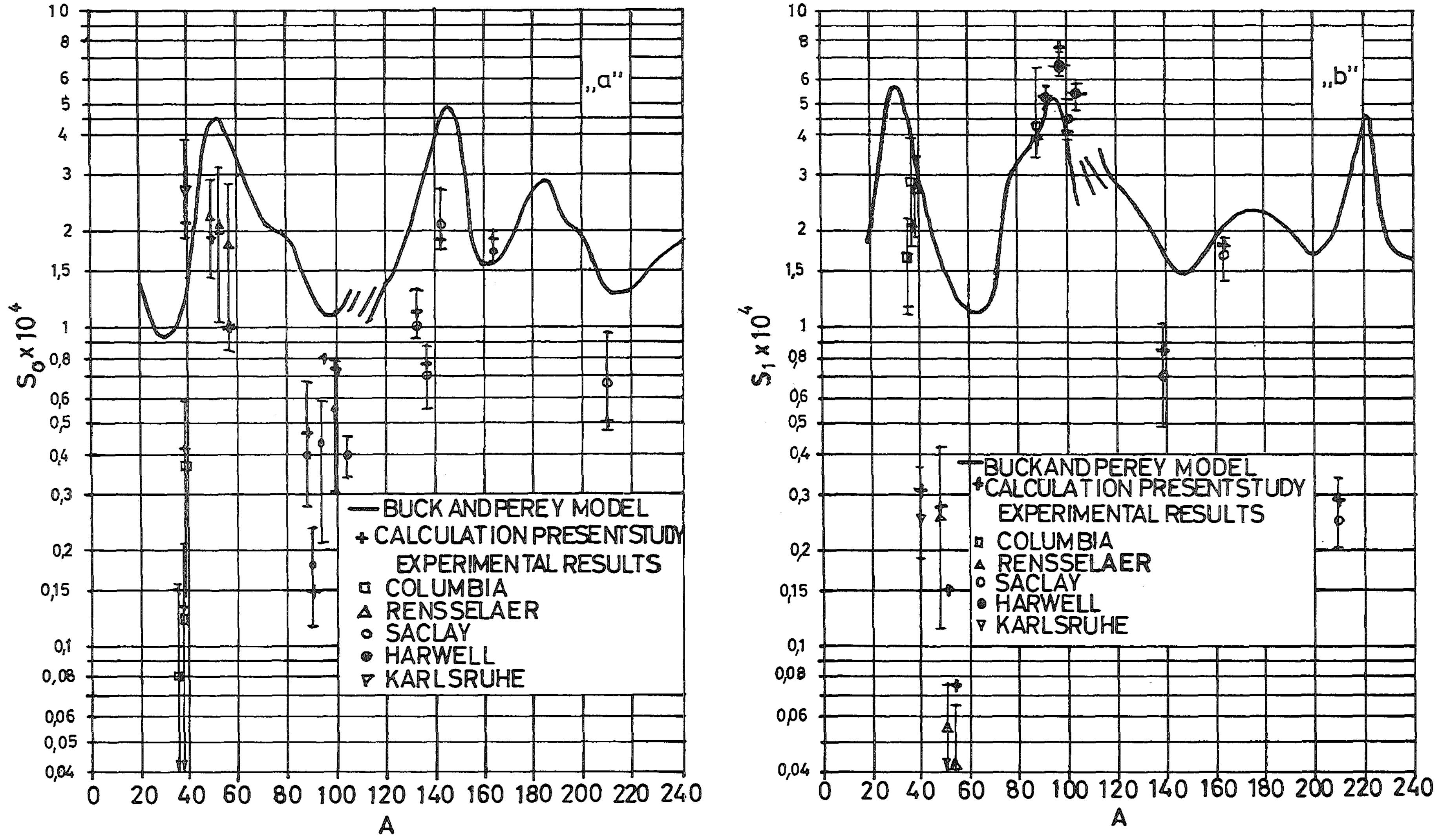

„a"
$S_0 \times 10^4$
A
BUCK AND PEREY MODEL
CALCULATION PRESENT STUDY
EXPERIMENTAL RESULTS
COLUMBIA
RENSSELAER
SACLAY
HARWELL
KARLSRUHE
„b"
$S_1 \times 10^4$
10
8
6
5
4
3
2
1,5
1
0,8
0,6
0,5
0,4
0,3
0,2
0,15
0,1
0,08
0,06
0,05
0,04
0
20
40
60
80
100
120
140
160
180
200
220
240

Fig. 5

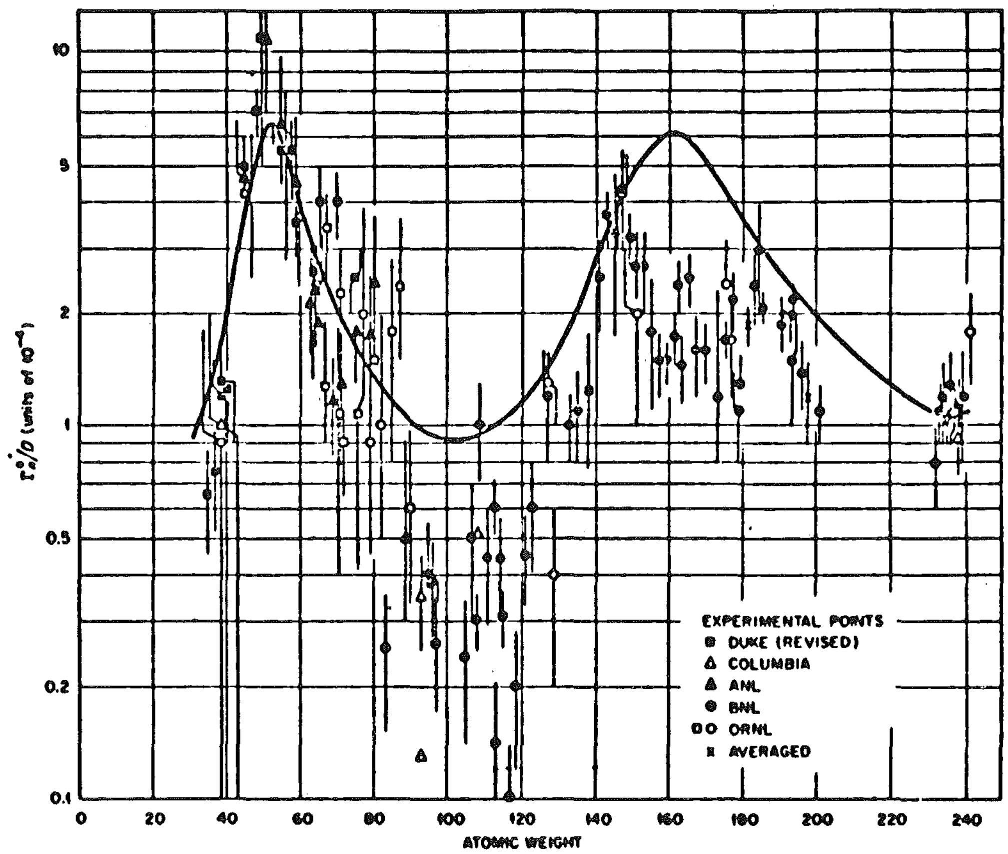

10
5
2
1
0.5
0.2
0.1
Γ_n^0/D (units of 10^{-4})
0
20
40
60
80
100
120
140
160
180
200
220
240
ATOMIC WEIGHT
EXPERIMENTAL POINTS
● DUKE (REVISED)
△ COLUMBIA
▲ ANL
● BNL
□○ ORNL
■ AVERAGED

Fig. 6

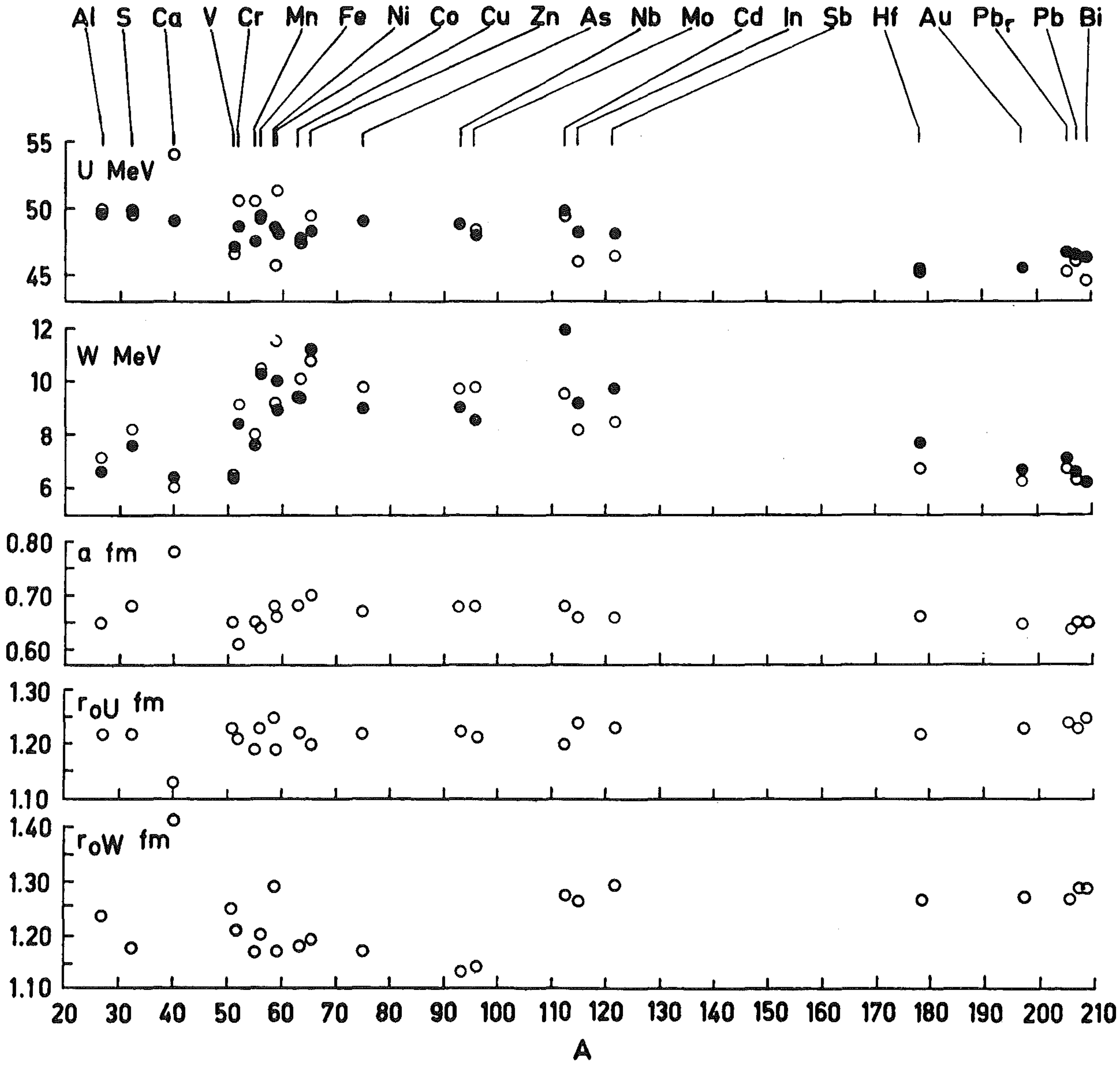

Al
S
Ca
V
Cr
Mn
Fe
Ni
Co
Cu
Zn
As
Nb
Mo
Cd
In
Sb
Hf
Au
Pb$_r$
Pb
Bi
U MeV
55
50
45
W MeV
12
10
8
6
a fm
0.80
0.70
0.60
r_oU fm
1.30
1.20
1.10
r_oW fm
1.40
1.30
1.20
1.10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
A

Fig. 7