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EVAPORATION OF NEUTRONS FROM STRONGLY EXCITED CLOSED SHELL $f_{7/2}$ NUCLEI IN INELASTIC NEUTRON SCATTERING

by

Józef Koralewski
Tadeusz Kozłowski
Zbigniew Moroz
Jolanta Wojtkowska

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EVAPORATION OF NEUTRONS FROM STRONGLY EXCITED CLOSED SHELL $f_{7/2}$ NUCLEI IN INELASTIC NEUTRON SCATTERING

WYPAROWANIE NEUTRONÓW Z SILNIE WZBUDZONYCH JĄDER O POWŁOCE ZAMKNIĘTEJ $f_{7/2}$, W NIEELASTYCZNYM ROZPRASZANIU

ИСПАРЕНИЕ НЕЙТРОНОВ ИЗ СИЛЬНО ВОЗБУЖДЕННЫХ ЯДЕР С ЗАМКНУТОЙ ОБОЛОЧКОЙ $f_{7/2}$, В НЕУПРУГОМ РАССЕЯНИИ НЕЙТРОНОВ

by

Józef Koralewski
Tadeusz Kozłowski
Zbigniew Moroz
Jolanta Wojtkowska

Abstract

Continuous spectra of neutrons inelastically scattered on V^{51}, Cr^{52}, and Ni^{58} have been measured with time - of - flight spectrometer at an incident energy of 14.1 MeV. The spectra were observed above the maximum energy of neutrons from the /n,2n/ reaction. From these spectra, the level density parameters T and a have been calculated. The results of investigations and comparisons with other measurements are as follows: /a/ the dominant reaction mechanism in the measured energy range is the evaporation of neutrons, /b/ the Fermi gas model gives a good approximation for nuclei with closed shell, /c/ there is evidence that the effect of pairing is insignificant at the studied excitation energy, /d/

the optical model reaction cross section seems to be a good expression for the inverse reaction cross section.

Streszczenie

Zmierzono ciągłe widma nieelastycznie rozproszonych neutronów na V^{51}, Cr^{52}, Ni^{58} spektrometrem czasu przelotu dla energii padających neutronów 14,1 MeV. Z części widma leżącej powyżej maksymalnej energii neutronów z reakcji /n, 2n/ obliczono parametry gęstości poziomów T i a.
Wyniki pomiarów i porównania z innymi eksperymentami są następujące: /a/ wyparowanie jest dominującą reakcją w mierzonym zakresie energii, /b/ model gazu Fermiego jest dobrym przybliżeniem dla jąder o zamkniętych powłokach, /c/ można przyjąć że efekt sparowania jest nieznaczny w badanym zakresie energii wzbudzenia, /d/ wydaje się że przekrój czynny na reakcję odwrotną dany przez model optyczny stanowi dobre przybliżenie.

Содержание

Методом времени пролета измерялись сплошные спектры неупруго-рассеянных нейтронов на V^{51}, Cr^{52}, Ni^{58}
при энергии нейтронов I4,I мэв. Из энергетического спектра выше максимальной энергии, из реакции рассчитано параметры плотности уровней Т и а. Результаты измерений и сравнение с другими экспериментами следующие:/а/ испарение является преимущественным процессом в измеряемом интервале энергии, /в/ модель Ферми газа является хорошим приближением для ядер с замкнутой оболочкой, /б/ можно предполагать, что эффект спаривания в исследованном интервале энергии незначителен, /д/ кажется, что формулаэффективного сечения обратимой реакции оптической модели является хорошим приближением.

INTRODUCTION

The evaporation model has existed from the first formulation [1], in 1936 of the statistical conception of nuclear reactions. Extensive detailed studies of this model have not been possible for a long period of time. The progress in experimental techniques and development of the theory have increased interest in this model.

The aim of this work was measurement of the level density parameters for strongly excited nuclei with magic number 28 of neutrons or protons V^{51}, Cr^{52}, Ni^{58}, and also determination of the dominant interaction in inelastic scattering of 14 MeV neutrons.

THEORY

The basic result of Bohr's conception of compound nucleus [2] is that the excited nucleus can be treated as a statistical system described in terms of a thermodynamical temperature t and corresponding state density. The thermodynamical approach to the nuclei has some limitations, namely: (a) the number of nucleons in the nucleus is as in typical thermodynamical systems, not very big, (b) the existence of the direct interaction process suggests local heating of the target nucleus.

In a statistical compound nucleus theory [3], the energy spectrum of evaporated particles is given by:

$$N(E)dE \sim \sigma_c(E)\cdot E\cdot \rho(U)dE , \qquad (1)$$

where U is the excitation of the residual nucleus, $\sigma_c(E)$ is the compound nucleus cross section for inverse reaction, and $\rho(U)$ is the level density of the residual nucleus for the excitation U.

A nuclear temperature T defined by:

$$\frac{1}{T}=\frac{d}{dU}\ln\,\rho(U) \qquad (2)$$

was commonly used to describe the experimental results. This value is approximatively equal to the thermodynamical temperature for high nucleus excitation.

The nuclear temperature T depends in general on the excitation energy U. In a relative small range of this energy, it may be treated as a constant, and thus:

$$\rho(U)\sim e^{U/T} \qquad (3)$$

The density of levels with an angular momentum J is given in a Fermi gas model of a nucleus by the following expression (4):

$$\rho(U,J)=\frac{(2J+1)}{(2cT)^{3/2}}\cdot\frac{1}{12\,a^{1/4}}\cdot exp[-(J+\tfrac{1}{2})^2/2\,cT]\cdot$$
$$\cdot(U+t)^{-5/4}\cdot exp\;2\sqrt{aU}, \qquad (4)$$

where c is a nuclear moment of inertia.

Integration of $\rho(U,J)$ over J leads to the total level density:

$$\rho(U) = \frac{1}{(2cT)^{1/2}} \cdot \frac{1}{12a^{1/4}}(U+t)^{-5/4} \exp 2\sqrt{aU} \qquad (5)$$

For high excitations, where $t \sim T \sim (U)^{1/2}$, this expression may be written as follows:

$$\rho(U) \sim \exp 2\sqrt{aU}/(U+T)^2 \qquad (6)$$

A Fermi free gas model does not take into account additional interaction between nucleons. The main effects of these interactions seem to be the pairing and shell phenomena. The results of many theoretical works indicate that the majority of the pairing effects can be interpreted in terms of a Fermi level shift [10]. For example, the dependence of the level density for small excitations on the number of neutrons or protons being odd or even can be obtained by decreasing the excitation energy by the term:

$$\Delta_p = \begin{cases} 0 \text{ for odd-odd nuclei} \\ \frac{1}{2}\Delta \text{ for even-odd and odd-even nuclei} \\ \Delta \text{ for even-even nuclei} \end{cases} \qquad (7)$$

$$\Delta = 3{,}36(1-\frac{A}{400}) \text{ for } A > 40 \text{ ,}$$

where Δp is the pairing energy required to uncondense the nuclear ground state.

The shell effects on the level density can be taken into account by the dependence of the level density parameter a on the average spins of neutron and proton states $\bar{j}_N$ and $\bar{j}_Z$ (5,6):

$$a = 0,0738(\bar{j}_N + \bar{j}_Z + 1)A^{2/3} \qquad (8)$$

EXPERIMENTAL PROCEDURE

Measurements were performed using a d-T neutron generator and a typical time-of-flight spectrometer [7], utilizing the associated particle method. The experimental arrangement is shown in Fig.1. A time-to-pulse height converter with a time range of 140 ns was used as a time analyser. Fig.2 shows the calibration curve of such converter. A neutron plastic detector was placed at a distance of 1m from the scatterer, at an angle of 90 degrees to the direction of the incident neutron beam. A detector threshold was fixed at approximately 700 keV proton energy. Scattering samples were cylinders 5 cm long and 3 cm in diameter.

Time spectra were corrected for detector efficiency and converted to energy spectra by the relation:

$$N(E) = \frac{t^3}{\varepsilon} N(t) \qquad (9)$$

The efficiency of the neutron detector was as in the work of J.E. Hardy [8], calculated by taking into account a second scattering of neutrons in a scintillator. Fig. 3

shows the results of numerical calculations for the efficiency at a threshold of 700 keV, and for a NE 102 scintillator 5 cm long. Reliability of this method was tested by measurement of the known spectrum of inelastically scattered neutrons on Bi scatterer.

A typical energy spectrum of neutrons is shown in Fig.4.

RESULTS

The energy of incident neutrons is higher than the threshold energy for (n,2n) reaction for all three nuclei. For this reason, only a part of the measured spectrum between a maximum energy of neutrons from the (n,2n)reaction and a maximum energy of neutrons measured with a good energy resolution, was taken for the interpretation of calculations.

From Eq. 1 one may obtain:

$$\varrho(U) \sim \frac{N(E)}{E \cdot \sigma_c(E)} \tag{10}$$

The experimental results were compared with the following expressions of the level density:

$$\varrho(U) = c e^{U/T} \qquad U = U_0 - E \tag{11}$$

$$\varrho(U) = c(U+T)^{-2} e^{2\sqrt{aU}} \qquad U = U_0 - E \tag{12}$$

$$\varrho(U) = c(U+T)^{-2} e^{2\sqrt{aU}} \qquad U = U_0 - E - \Delta_p \tag{13}$$

The correct interpretation of continuous spectra in terms of the level density requires a fairly good knowledge of the energy variation of the inverse cross section $\sigma_c(E)$ Two different forms for $\sigma_c(E)$ were used:

(a) $\sigma_c(E)$ = const, as is usually assumed,

(b) $\sigma_c(E) = \pi t^2 \sum_l (2l+1)T_l$, an optical model reaction cross section.

The values of the transmission coefficients T_l were taken from the Emmerich tabels [9]. It must be pointed out that the optical model concerns the nuclei in the ground state, and $\sigma_c(E)$ in Eq.(10) relates to the inverse cross section for excited nuclei. However, the optical model parameters are not expected to be different for excited nuclei and nuclei in ground state. Fig.(5) shows the optical model reaction cross section used in our calculations of the level density parameters.

To determine the values of the nuclear temperature T, the quantity $ln \frac{N(E)}{E \cdot \sigma_c(E)}$ was plotted against E. If the level density is described by Eq.(11), this plot should be linear with a slope $-\frac{1}{T}$. Such plots are shown in Figs. 6,7 and 8.

To determine the values of the level density parameter a, the quantity $ln(U+T)^2/E \cdot \sigma_c(E)$ was plotted against $\sqrt{U}$ for the two expressions for U mentioned above. A slope of such lines should be equal to $2\sqrt{a}$. Figs. 9, 10 and 11, shows the results. The parameters T and a were calculated using the least square method. They are listed in Table 1.

The values of the parameter a could be obtained from the expression:

$$a = \frac{\bar{U}}{T^2} + \frac{4\bar{U}}{T(\bar{U}+T)^2} + \frac{4\bar{U}}{(\bar{U}+T)^2}, \qquad (14)$$

which results from differentiation of Eq. 6 . $\bar{U}$ is the mean excitation energy of the nucleus. However, the exact values of this energy are not known.

The errors in Table 1 involve:

a) statistical errors of experimental points,

b) the accuracy of calibration and linearity and of the finite time resolution of the time analyser,

c) the accuracy of calculation of efficiency.

The correction for multiple scattering was neglected because of the experimental conditions of the measurement.

DISCUSSION

The values of the level density parameters T and a measured in this work relate to the mean excitation energy of about 10 MeV.

It is known from measurements of the ratio Γ_p/Γ_n for many nuclei in this region of A that a mean nuclear temperature T for the excitation energy 11 MeV, is equal to 1.58 MeV [10]. From measurements of slow neutron resonances [11], such temperature for V^{51} is equal to 1,6 MeV. These values are in very good agreement with our results for the optical model inverse cross section.

It is clear from this comparison that a contribution of direct interaction should be small in the energy range of inelastically scattered neutrons, because the existence of this contribution should give higher values of temperatures. The small contribution of the direct interaction results from the angle of scattering which was used in these measurements.

A number of measurements (11,12,13) of the level density parameters for V^{51} for different excitations have been mach. The mean excitation energy relates to these parameters by Eq. 14 , or by:

$$\overline{U} = aT^2 - 4T + \Delta p \qquad (15)$$

A plot of $(\overline{U}+4T-\Delta p)$ versus T should be linear 6 with a slope which is equal to a. Fig.12 shows such a plot, where data for the d,p and p,p′ reactions are taken from (12), for the (n, γ) reaction from (11), and for the n,n′ reaction from (13) and our present work. The results of work [13] were recalculated by us assuming the optical model inverse cross section. Our value of T was calculated for the same assumption. These results represent a straight line, and the value of a obtained from this plot is equal to 7.3 MeV^{-1}.

The following conclusion may be drawn from this diagram: the level density parameter a is constant in a large range of excitations: that means that the Fermi gas model of the level density is the best approximation for the closed shell nucleus. However, it is impossible to learn from this plot whether the value of a Fermi level shift Δp chosen by us is really valid.

The values measured of the level density parameter a were compared with a semi-empirical curve obtained from Eq. 8 . Fig. 13 shows that this curve agrees very well with our results for the optical model reaction cross section used for $\sigma_c(E)$, and at $\Delta p = 0$. The variant of $\sigma_c(E)$ = const must be definitely rejected. For $\Delta p \neq 0$ the agreement is somewhat less correct , and it seems that decrease of the influence of the pairing interaction on the level density observed in works [14, 15] has been confirmed in the present work.

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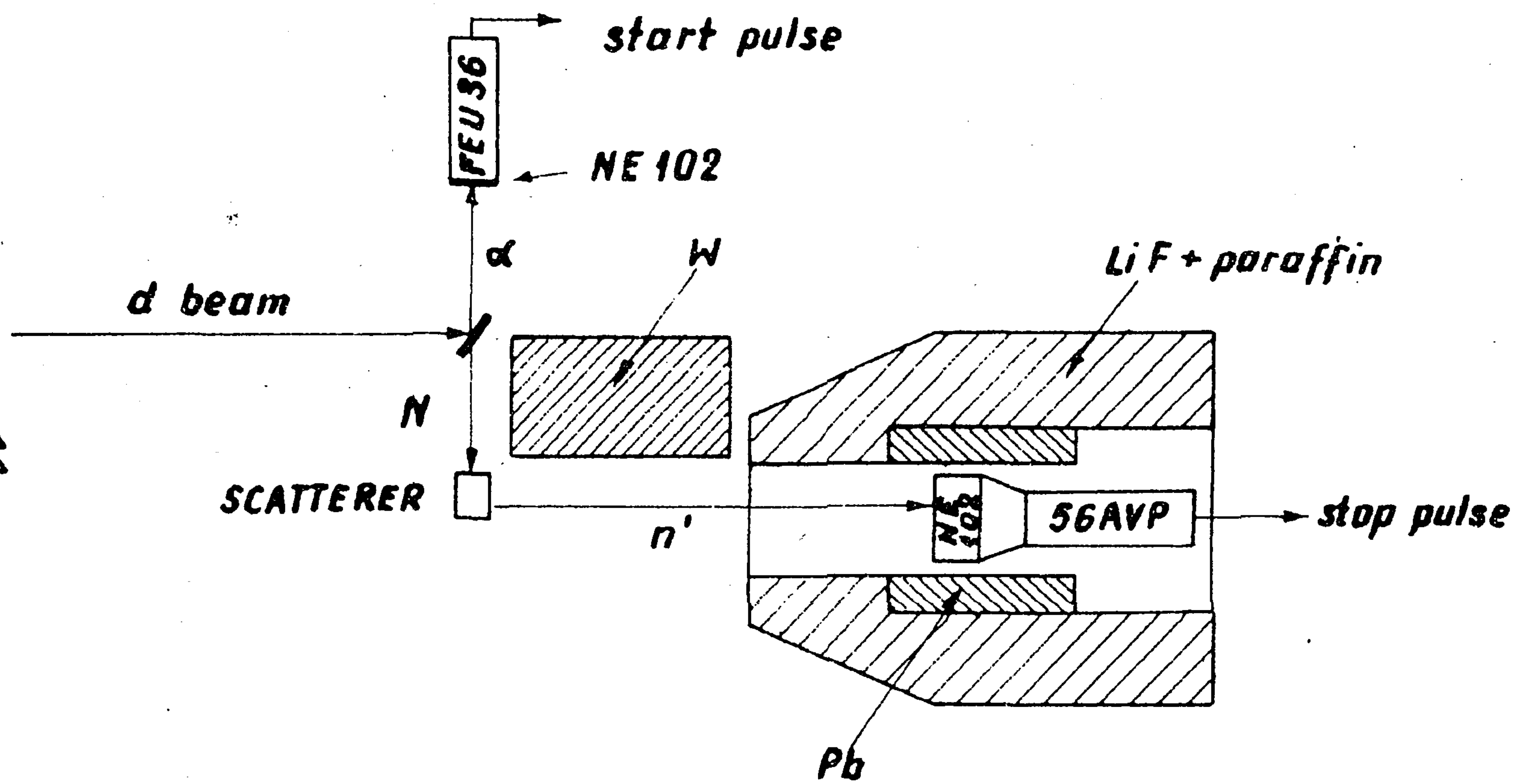

Fig. 1 Experimental arrangement

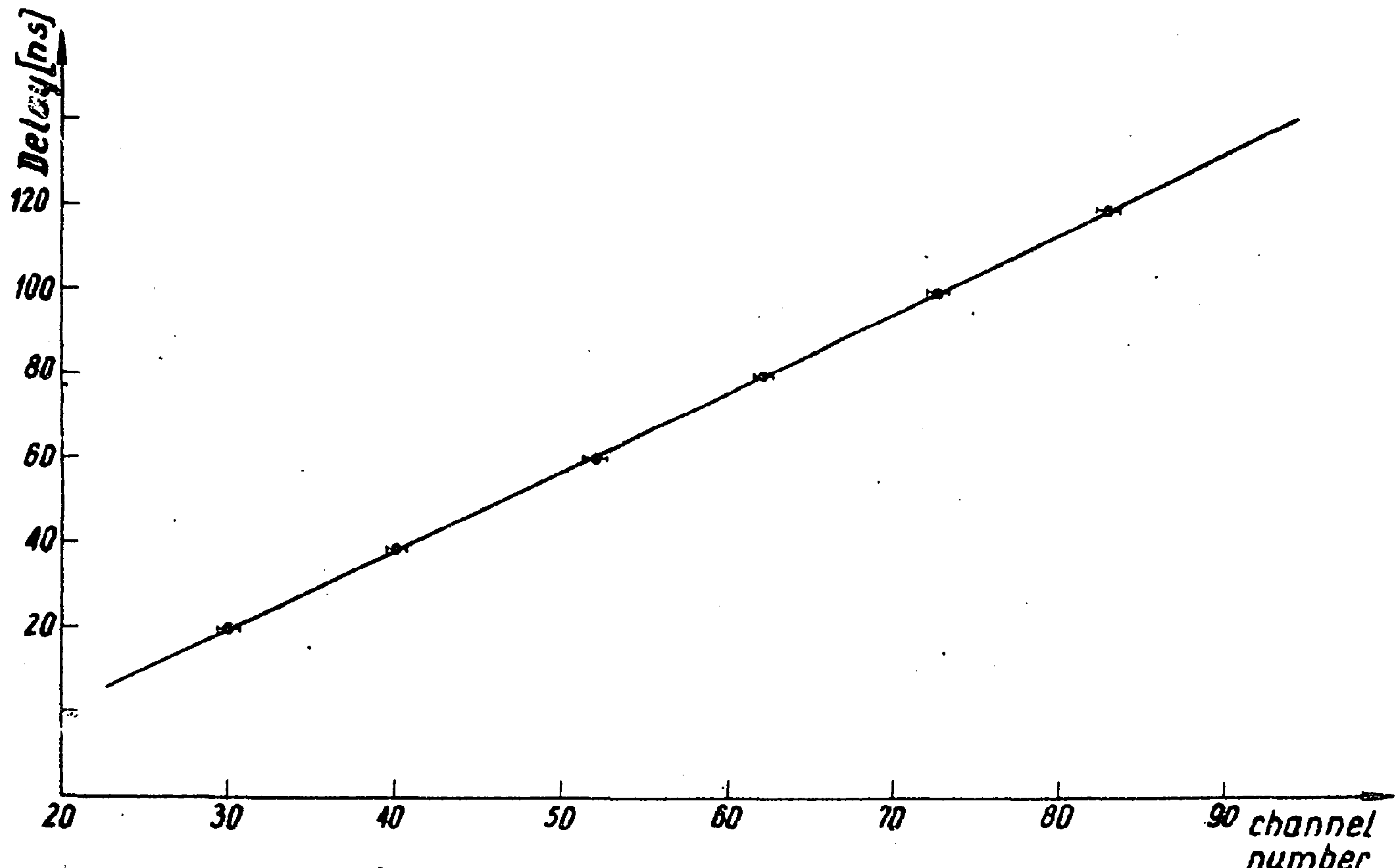

Fig.2. Calibration curve of t-p.h converter

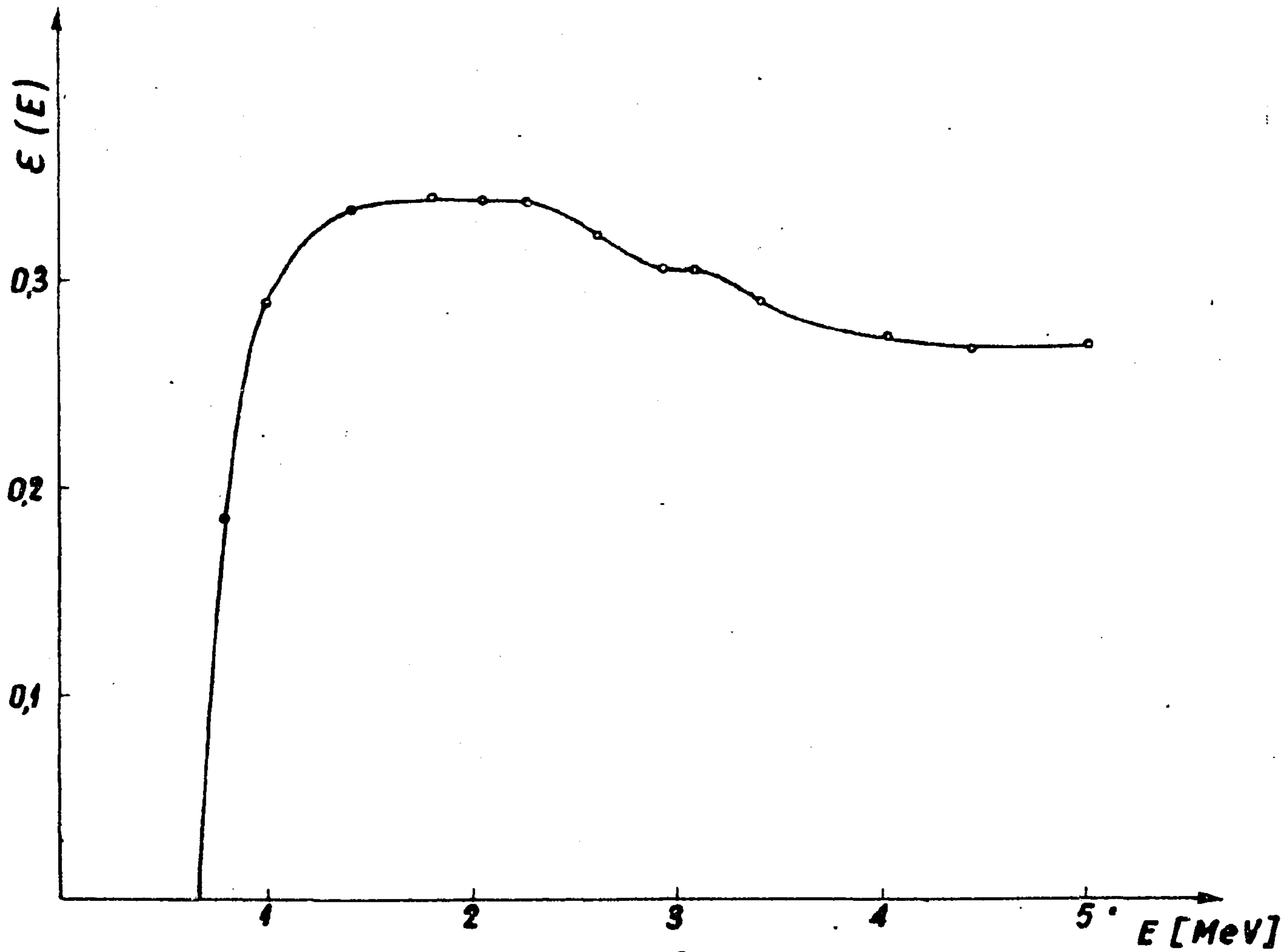

Fig.3 Efficiency of the plastic scintillator

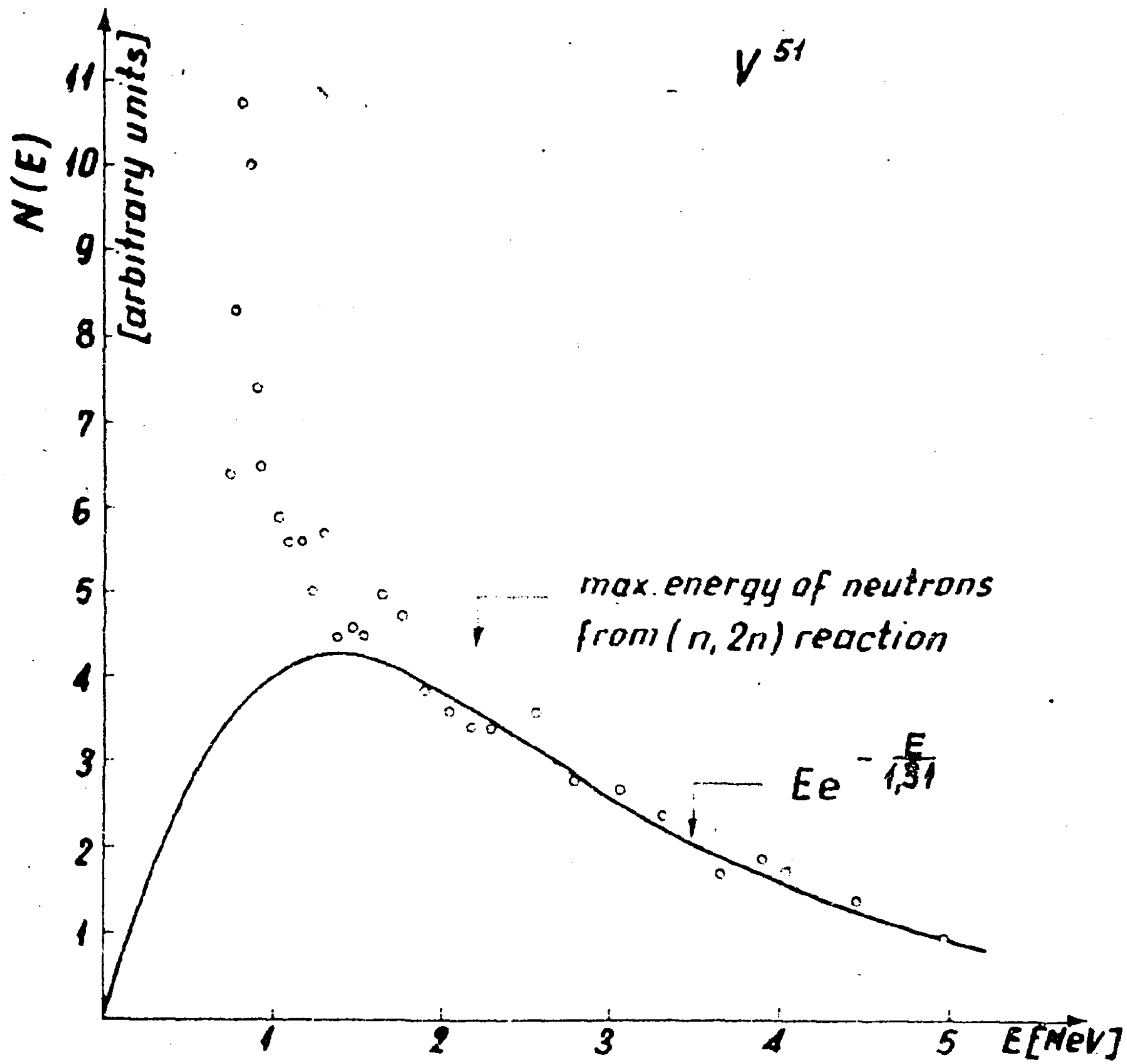

Fig. 4 Typical energy spectrum

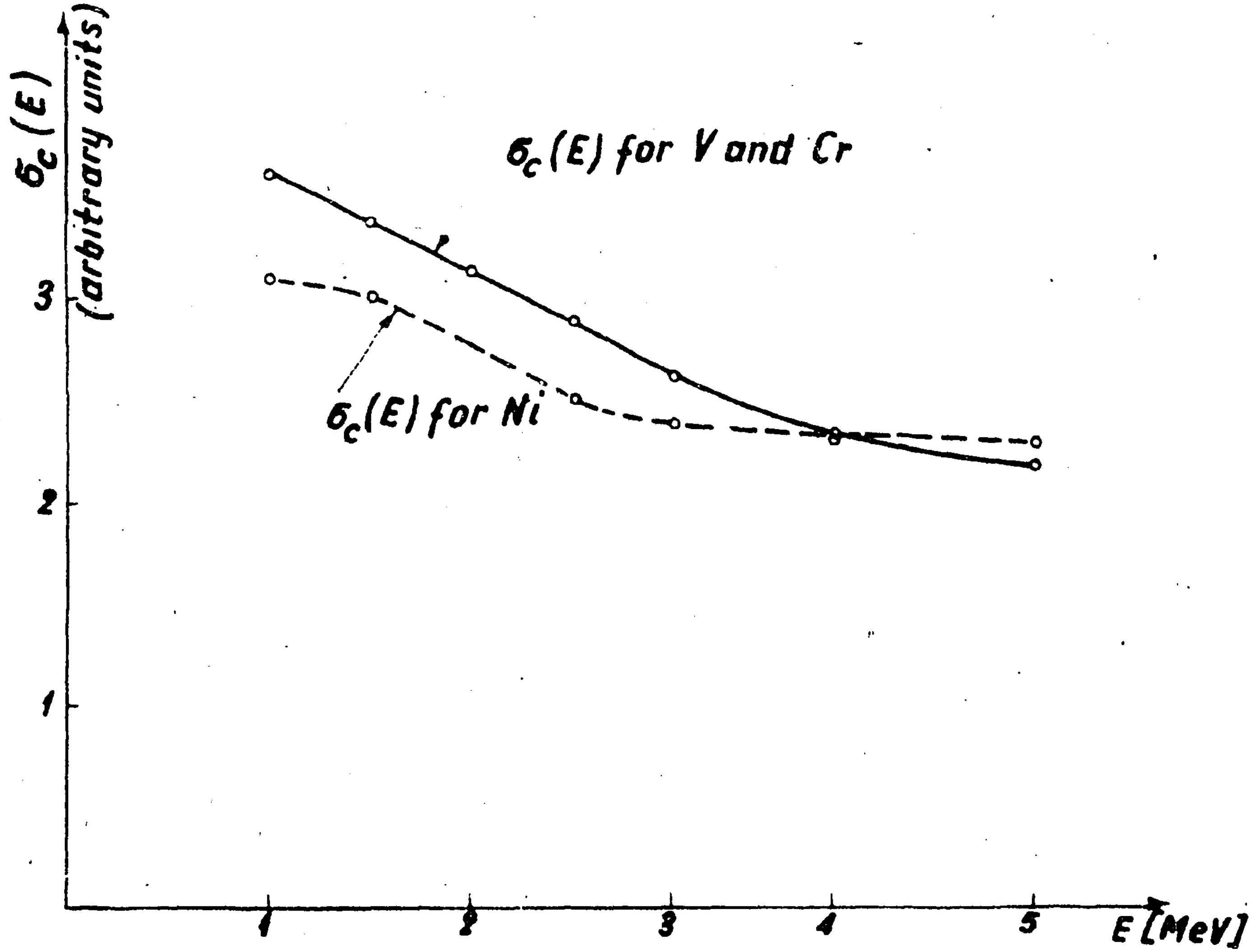

Fig.5 Optical model cross sections $\sigma_c(E)$

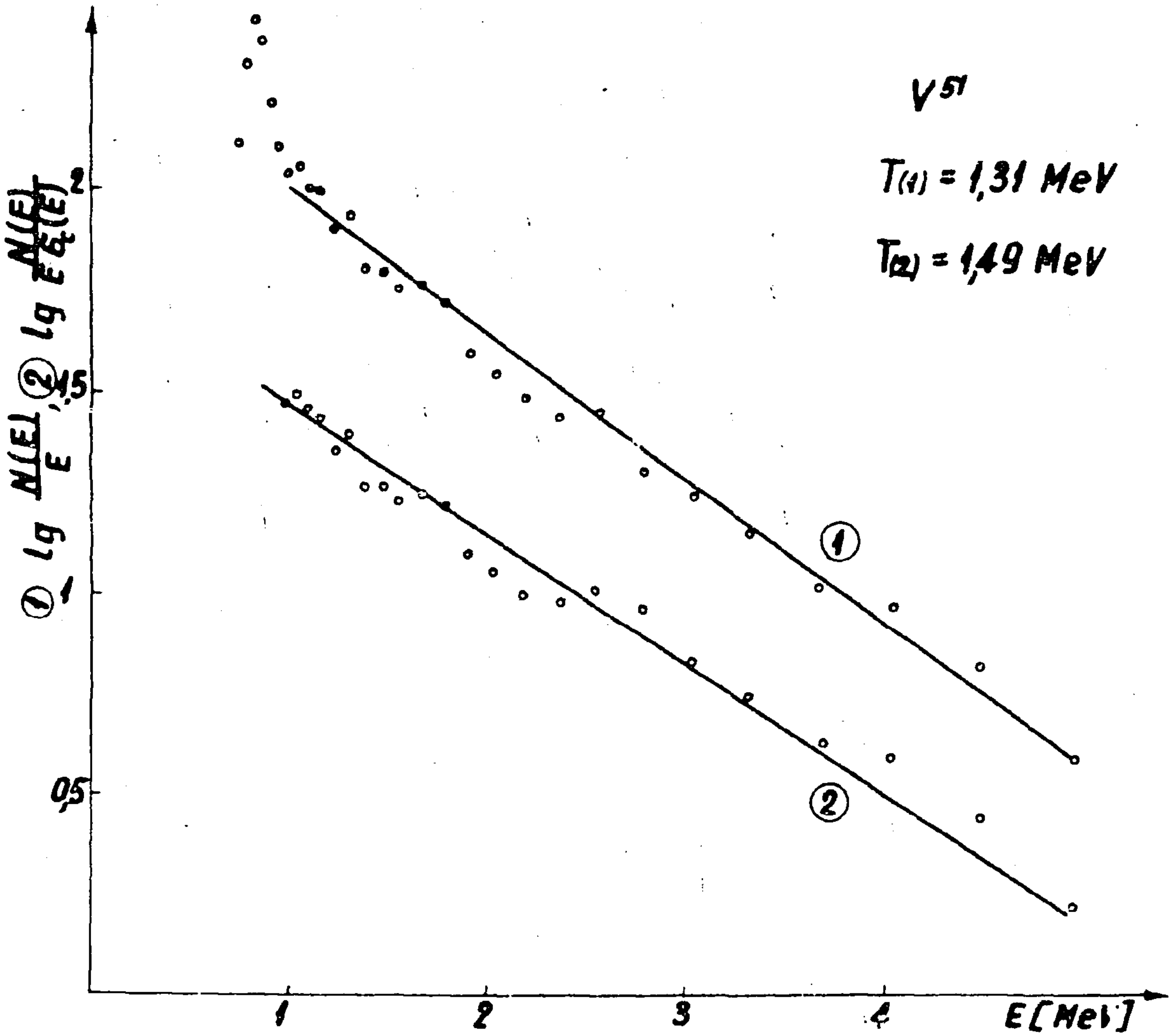

Fig. 6 Plots of $\lg \frac{N(E)}{E}$ and $\lg \frac{N(E)}{E\,\sigma_c(E)}$ for vanadium

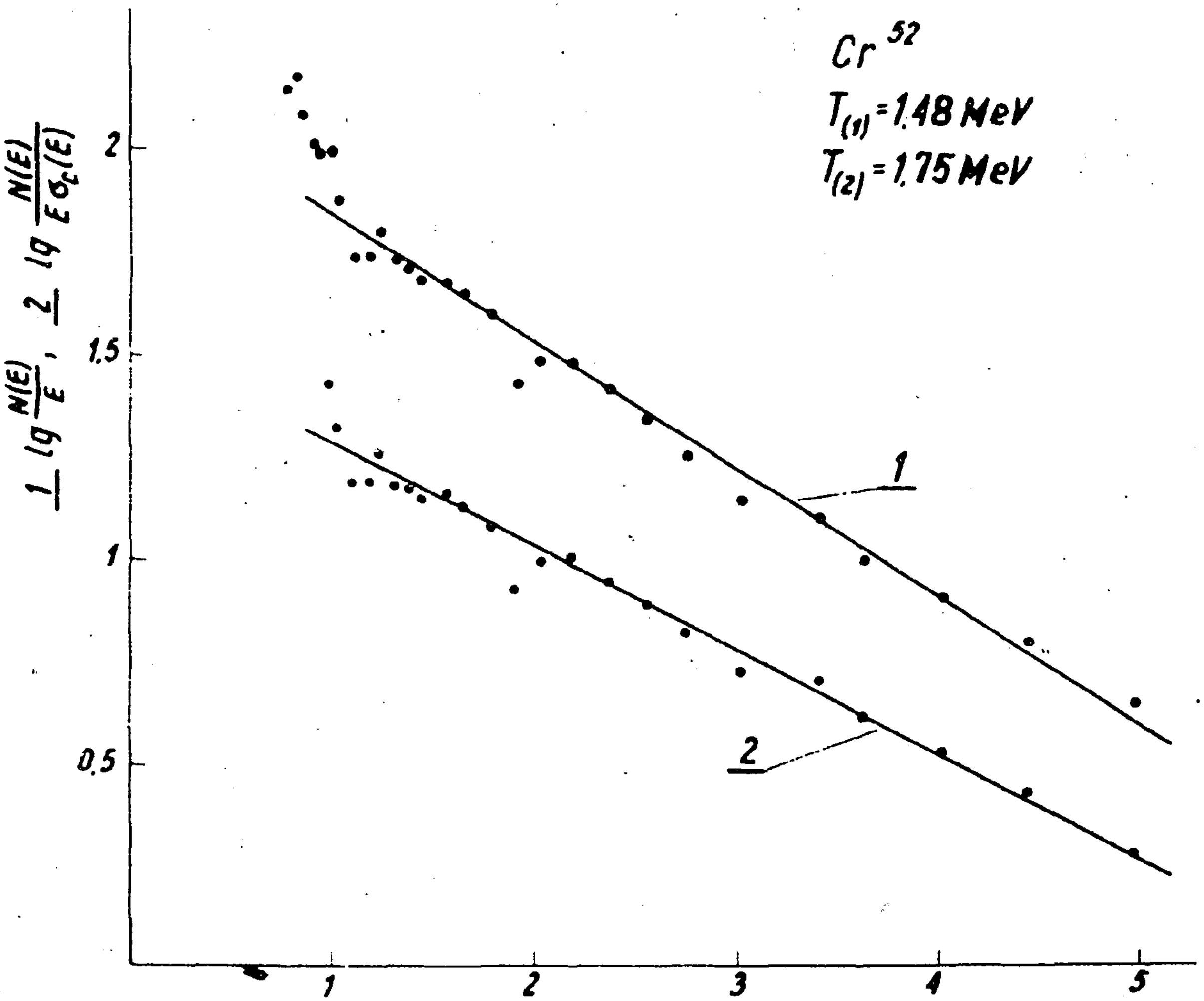

Fig. 7. Plots of $\lg\frac{N(E)}{E}$ and $\lg\frac{N(E)}{E\sigma_c(E)}$ for chromium.

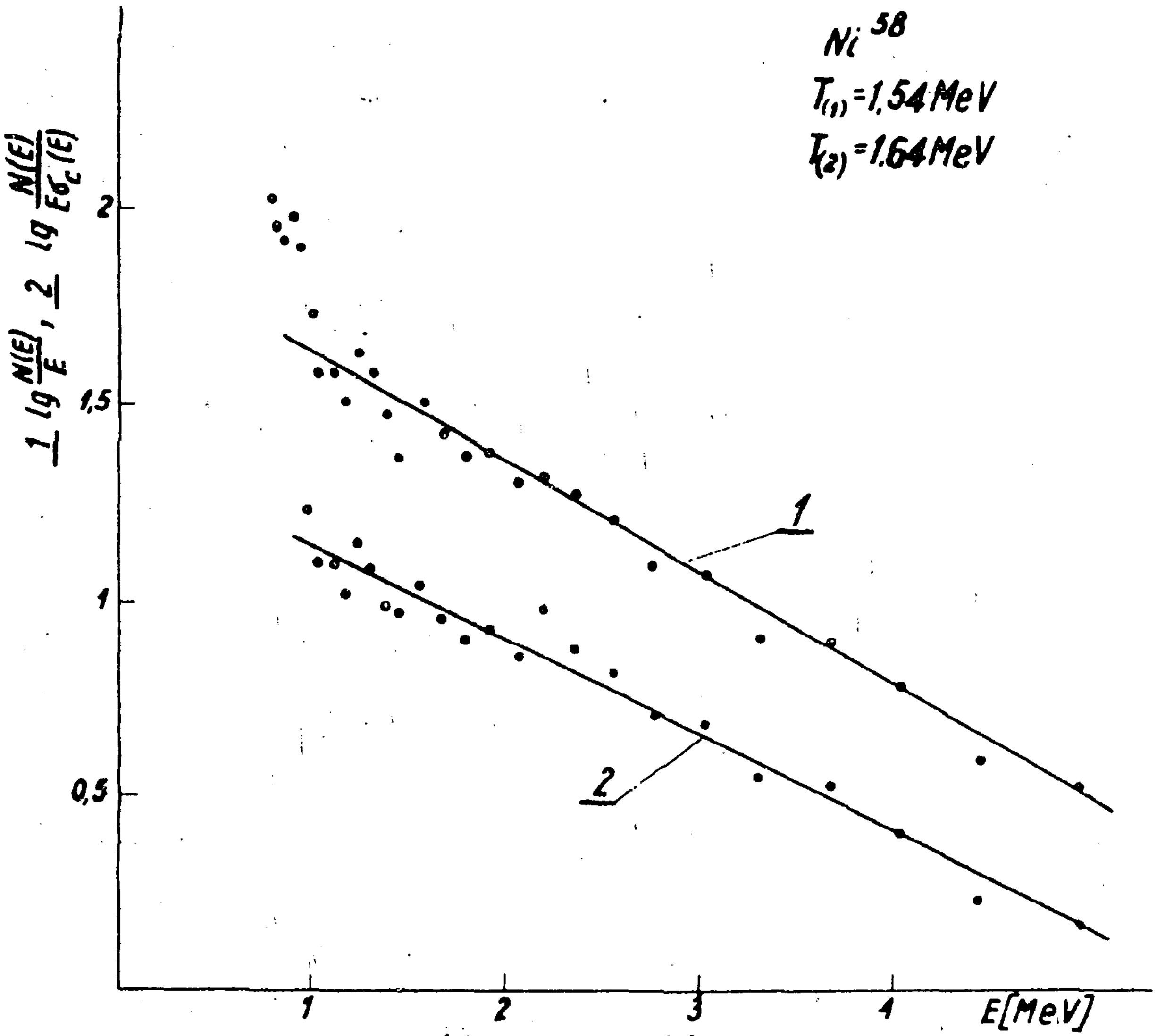

Fig. 8. Plots of $\lg \frac{N(E)}{E\sigma_c(E)}$ and $\lg \frac{N(E)}{E}$ for nickel.

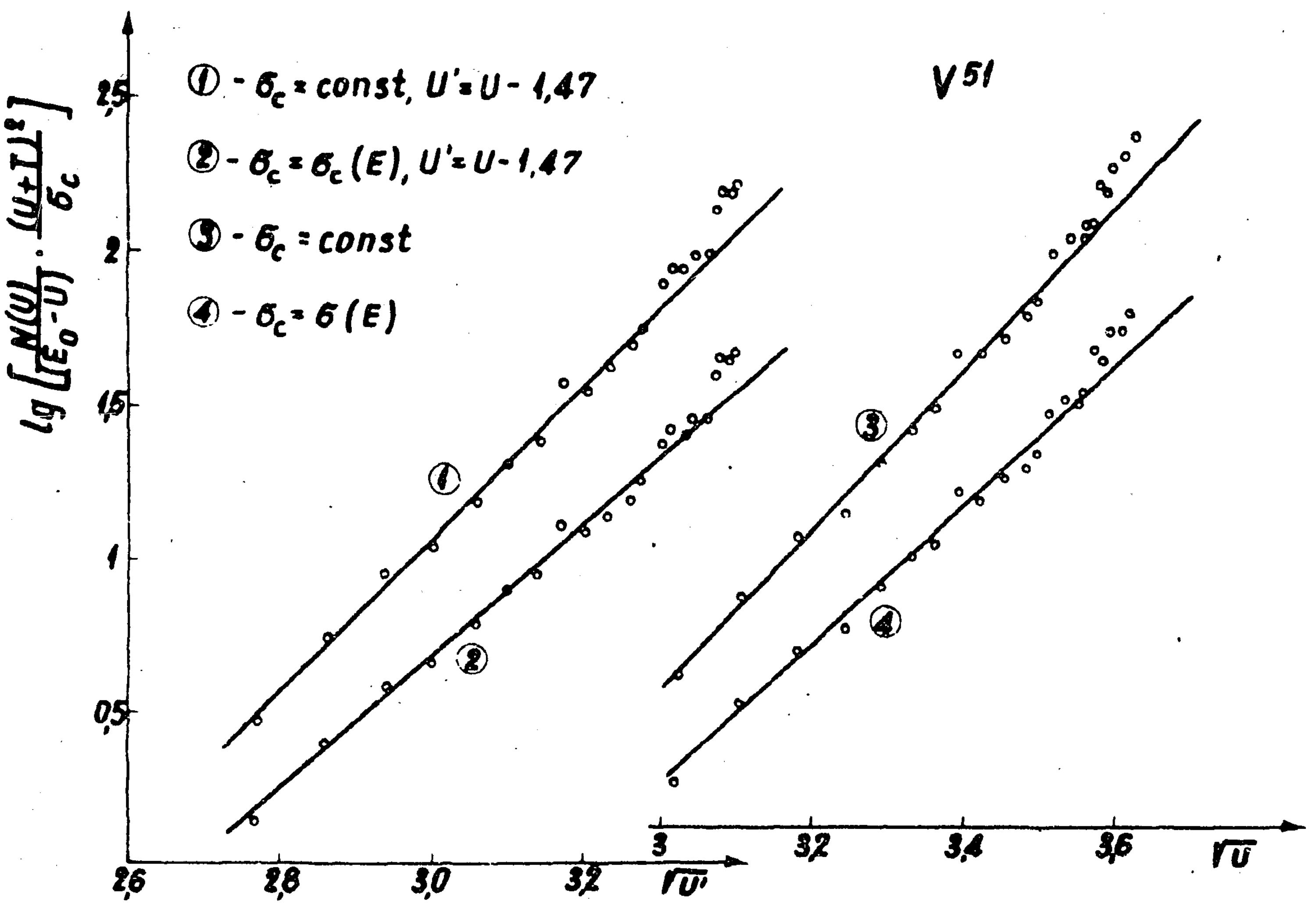

Fig. 9 Plots of $\lg\left[\frac{N(U)}{E_0-U}\cdot\frac{(U+T)^2}{\sigma_c}\right]$ for vanadium

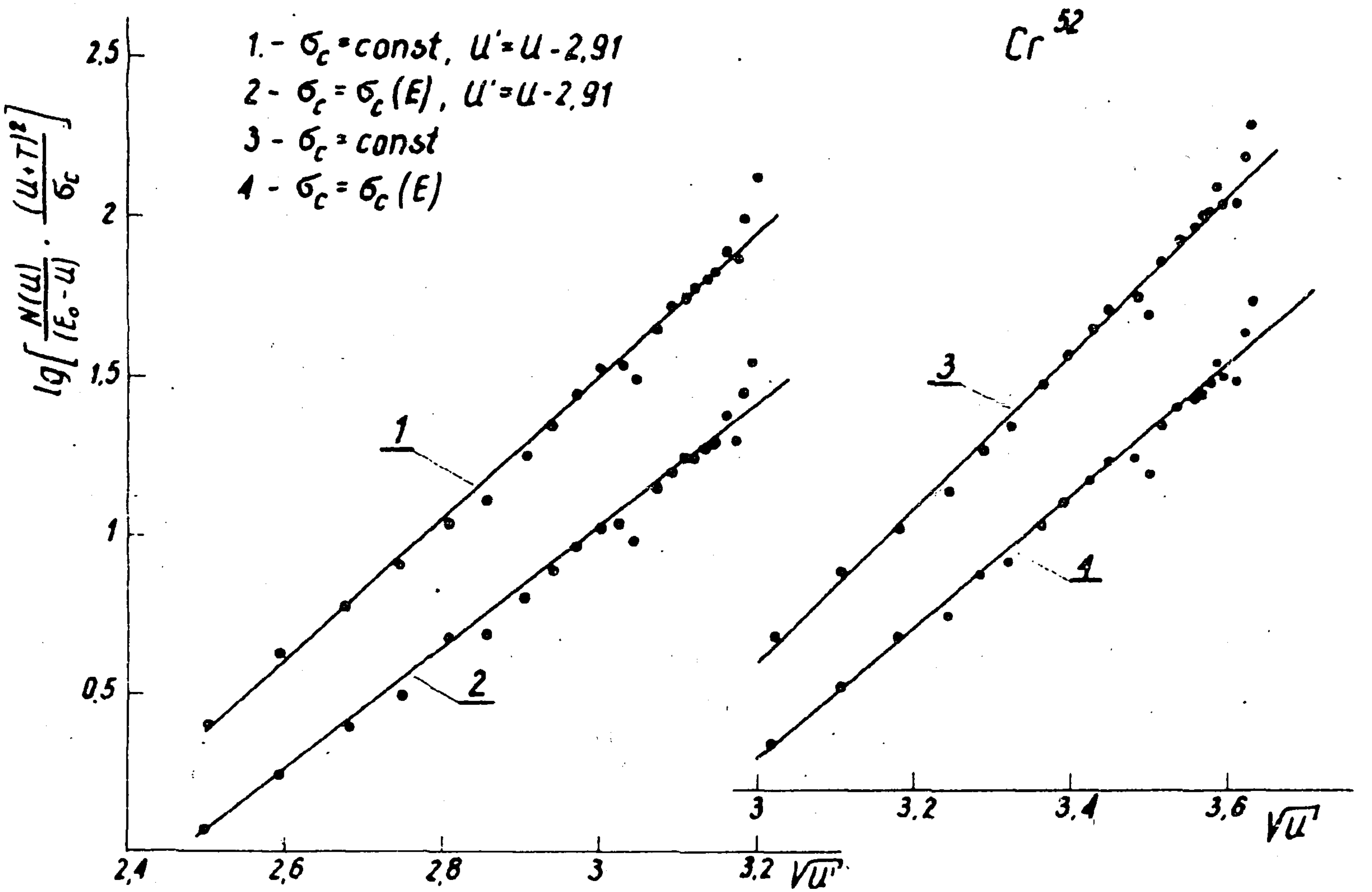

Fig.10. Plots of $\lg\left[\frac{N(U)}{E_0-U}\cdot\frac{(U+T)^2}{\sigma_c}\right]$ for chromium.

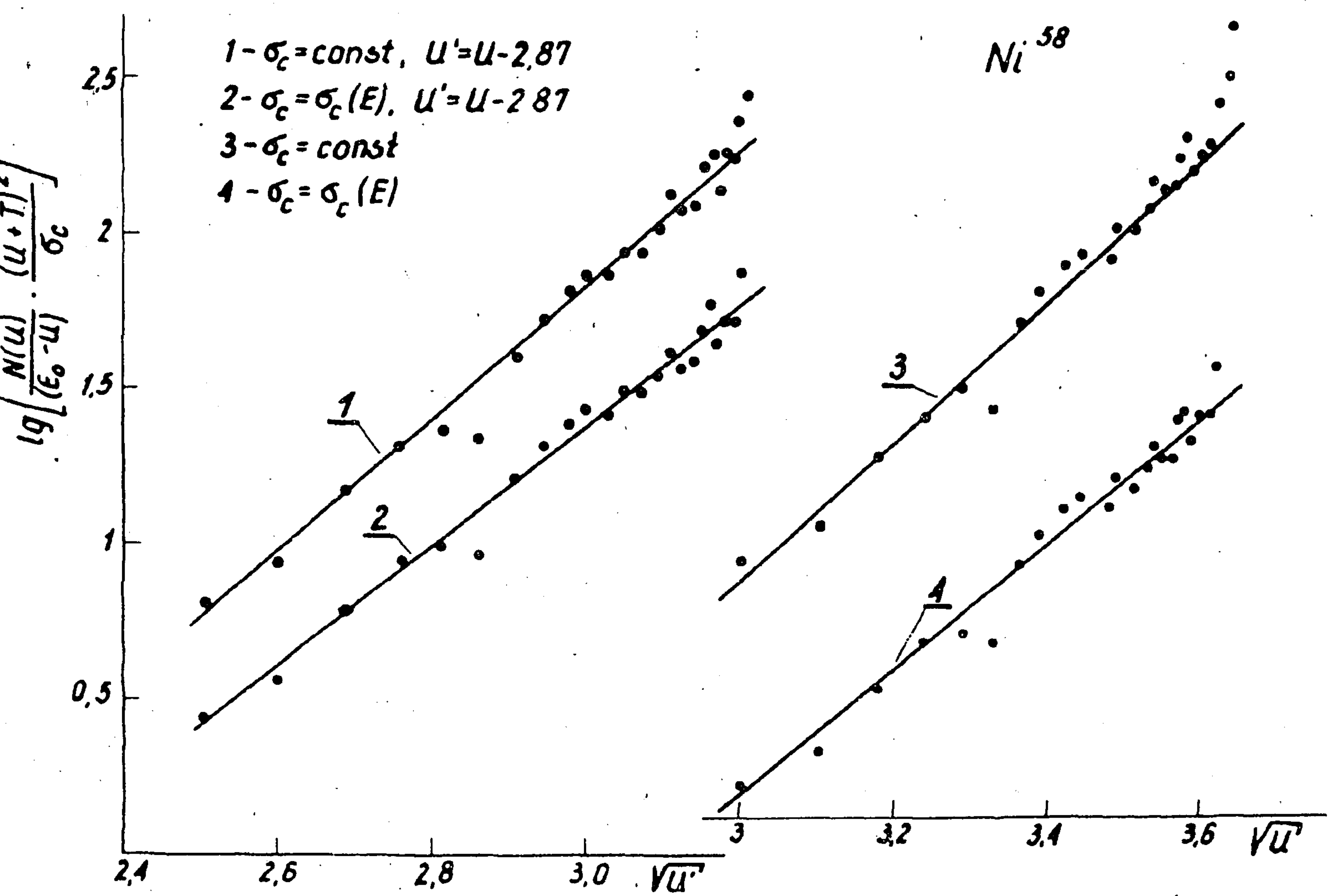

Fig. 11. Plots of $lg\left[\frac{N(U)}{(E_o - U)} \cdot \frac{(U+T)^2}{\sigma_c}\right]$ for nickel.

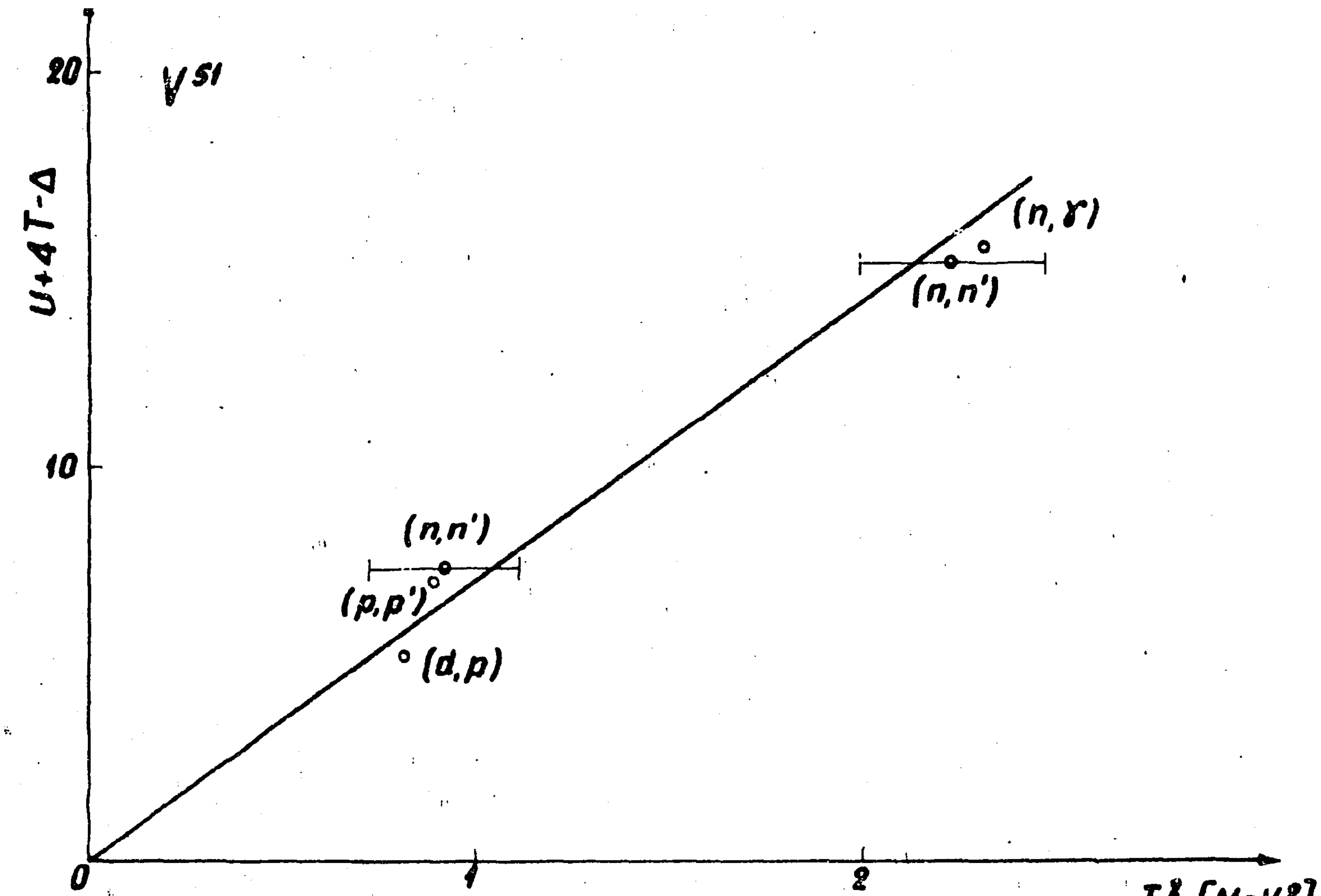

Fig. 12 Plot of $U+4T-\Delta$ vs. T^2.
$\sigma_c = \sigma_c(E)$ for (n,n')

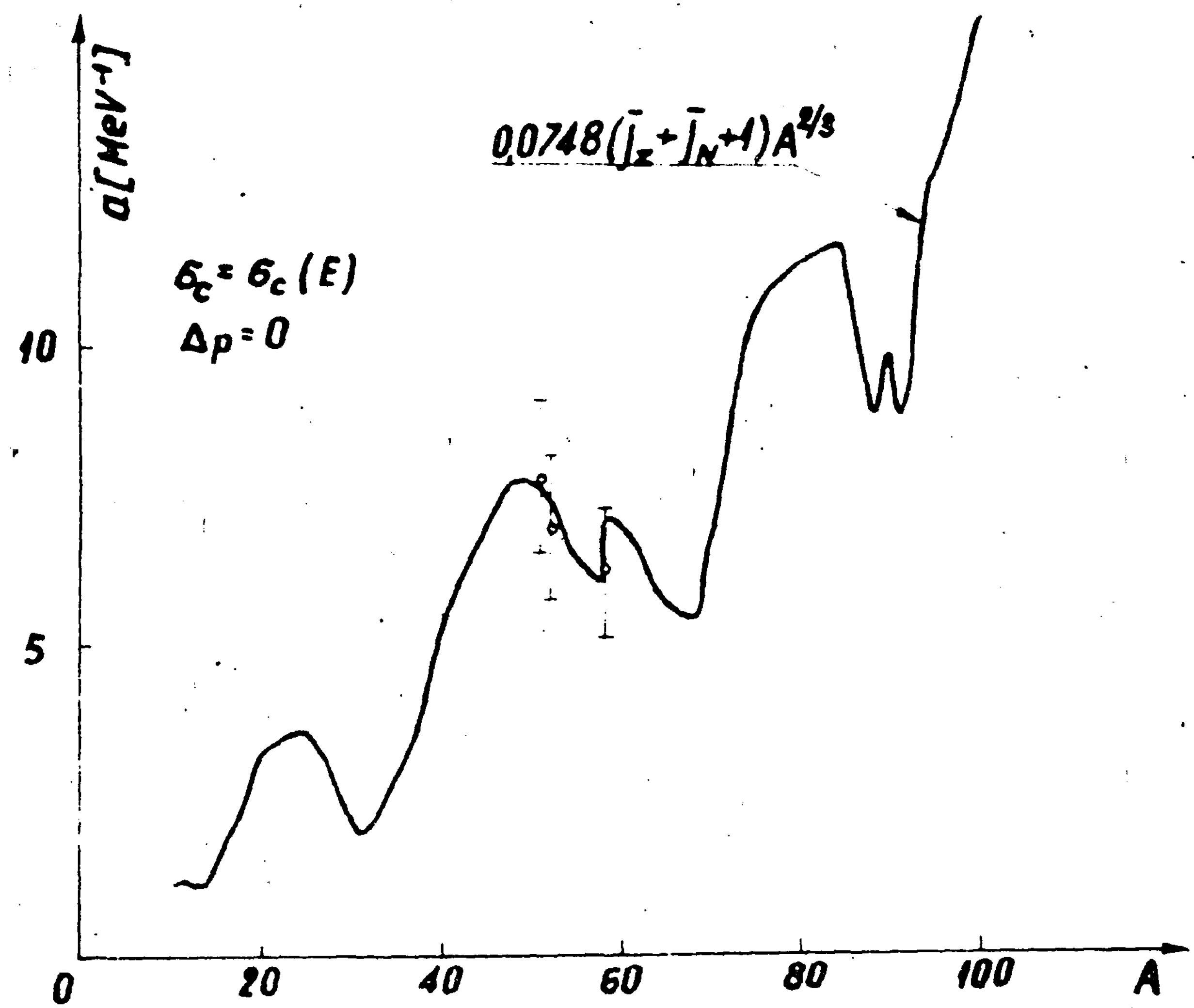

Fig. 13 Level density coefficient vs mass number

	Δ_p	a (± 15 %)				T (± 8 %)	
		$\Delta_p = 0$ $\sigma_c = const$	$\Delta_p = 0$ $\sigma_c = \sigma_c(E)$	$\Delta_p \neq 0$ $\sigma_c = const$	$\Delta_p \neq 0$ $\sigma_c = \sigma_c(E)$	$\sigma_c = const$	$\sigma_c = \sigma_c(E)$
V^{51}	1,47	9,9	7,8	8,3	6,4	1,31	1,49
Cr^{52}	2,91	8,4	6,1	7,6	5,9	1,48	1,75
Ni^{58}	2,87	5,9	5,5	4,8	4,8	1,54	1,64