NUCLEAR LEVEL DENSITIES OF ^{165}Er AND ^{181}W

B.V.Zhuravlev

State Scientific Center of Russian Federation - Institute of Physics and Power Engineering, 249020 Obninsk, Kaluga Region, Russia

ABSTRACT

The absolute value, energy dependence, spin cut-off factor of the nuclear level density for nuclei of ^{165}Er and ^{181}W have been determined from analysis of the experimental data on evaporation spectra, S-wave neutron resonances and spins of low-lying levels. The obtained results on nuclear level densities are in a good agreement with low-lying states and with calculations on the generalized superfluid model of nucleus in the excitation energy range of (0-9) MeV. For ^{165}Er the steplike structure in energy dependence in the range of (2-5) MeV is found. It is shown that the spin cut-off parameter and effective moment of inertia correspond to their rigid body values and energy dependence of the effective moment of inertia confirms the non-interacting fermion model prediction.

INTRODUCTION

Information on the nuclear level density, its energy and spin dependences is very important for both the creation of consistent theoretical description of excited nucleus properties and the nuclear reaction cross-section calculations within the framework of statistical model of nuclear reactions for many branches of nuclear physics, nuclear astrophysics and applied areas. The nuclear level density is presented in the generalized superfluid model of nucleus in the following way [1]:

$$\rho(U,J) = K_{vib}(U)\cdot K_{rot}(U)\cdot \rho_{BCS}(U,J), \qquad (1)$$

where $\rho_{BCS}(U,J)$ is the density of internal excitations in the superfluid model, K_{vib} and K_{rot} are collective enhancement factors, vibrating and rotating respectively.

The dependence of the nuclear level density ρ from the angular momentum J can be written as

$$\rho_{BCS}(U,J) = \frac{(2J+1)}{2\sigma^2}\exp(-\frac{J(J+1)}{2\sigma^2})\cdot \rho_{BCS}(U), \qquad (2)$$

where σ is the spin cut-off factor describing the width of distribution, U is the excitation energy. According to Ericson [2]

$$\sigma^2 = g < m^2 > t = (I_{eff}/\hbar^2)t, \qquad (3)$$

where g is the density of single particle states, t is the temperature, $<m^2>$ is the average of the square of the spin projection for single particle states near the Fermi level. The value $<m^2>g$ is called the effective moment of inertia.

Experimental information about spin cut-off parameter or its equivalent "effective moment of inertia" is derived, mainly, from the measurements of angular distributions of particles emitted in compound nuclear reactions and isomer ratios. However the anisotropy of the angular distributions for such heavy nuclei is very small and can not be measured reliably, and in case of the isomer ratio measurements it is not clear how correctly to treat the γ - cascade feeding the isomeric states. Perhaps that is why the available experimental data on effective moment of inertia for ^{181}W [3] obtained from the measurements and analysis of the neutron angular distributions in nuclear reaction ^{181}Ta(p,n)^{181}W is lower its rigid body value in 10 times.

In the present work the nuclear level densities of ^{165}Er and ^{181}W have been determined in a wide excitation energy range from the measurements and analysis of the neutron emission spectra in (p,n) reaction, and from comparison of level density at neutron binding energy with the average S-wave neutron resonance spacing data the spin cut-off factor and effective moment of inertia have been found. At low excitation energy the spin cut-off factor was determined also from approximation of the well-known low-lying level distributions on spin by the statistical distribution.

MEASUREMENTS AND DATA ANALYSIS

The nuclear level densities of ^{165}Er and ^{181}W and their energy dependences at excitation energy range of (0-9) MeV were determined from the measurements of neutron emission spectra in (p,n) reaction and theirs analysis within the framework of the statistical model of nuclear reactions. The measurements of neutron spectra were performed by time-of-flight method on the tandem accelerator EGP-10M and 150 cm cyclotron of IPPE [4,5,6] at proton energy range of (7-11) MeV. As a targets the selfsupporting metal foils were used with thickness of 13.66 and 19.86 mg/cm^2, respectively for ^{165}Ho and ^{181}Ta, and enrichment of 99.9%. Neutrons were detected by the scintillation detector based on a stilben cristal with pulse shape (n-γ) discrimination. The detector efficiency was determined by measuring of the ^{252}Cf prompt fission neutron spectrum by the time-of-flight method with fission fragment registration by a fast ionization chamber. The neutron spectrum measurement procedure has been consisted in measuring with a target and without it for the same proton flux registrated by the current integrator with Faraday cup as a charge collector. The background was almost negligible and uncorrelated in time. The angle-integrated neutron spectrum used for level density analysis was derived from the measured differential spectra and the experimental uncertainties in it were from 5 to 15% depending on neutron energy. The method of nuclear level density determination from the neutron emission spectra is based on the fact that the nuclear level density is one of the most critical component of statistical model calculations. In the present work the analysis of the measured neutron spectra have been carried out by means of Hauser-Feshbach calculations with the generalized superfluid model of nucleus for nuclear level density. The procedure of nuclear level density determination consisted in following:

1. The model parameters of the level density are adjusted such that the cross-section calculated by means of Hauser-Feshbach formula fits the measured value in the energy range of discrete levels. It means that the total decay width of compound nucleus is determined,
2. Using the chosen model of the level density the differential cross-section for continuum part of spectrum is calculated and absolute level density is determined in a wide range of excitation energy from comparison of the spectra measured and calculated

$$\rho(U) = \rho(U)_{\mathrm{mod}\,el} \frac{(d\sigma / dE_n)_{meas}}{(d\sigma / dE_n)_{calc}} \qquad (4)$$

All calculations in the framework of an optic-statistical approach have been carried out with the SMT-80 code [7] allowed to observe compound nucleus decay with taking into account all possible channel of emission. At low excitation energies of the residual nucleus the transitions to discrete levels have been taken into account and the calculated cross-sections for the comparison with the experimental data have been averaged over the excitation energy in line with normal law. The dispersion of the distribution corresponded to the spectrometer resolution. The calculations have been carried out with global systematics of optical potential obtained in the work [8,9]. The proton optical potential parameters [8] varied within a small range so that the calculated absorption cross-sections corresponded to the measured data.

The nuclear level densities of ^{165}Er and ^{181}W in the excitation energy range of (0-9) MeV determined from the measurements and analysis of neutron evaporation spectra in reactions ^{165}Ho(p,n)^{165}Er and ^{181}Ta(p,n)^{181}W are shown in figs.1,2. The uncertainty of the level density is ~20%. The knowledge of the nuclear level density at neutron binding energy B_n and the average S-wave neutron spacing $<D_{1/2+}>$ allow to determined the spin cut-off parameter

$$\sigma^2 = \rho(B_n) < D_{1/2+} > /2 \qquad (5)$$

and according to (2) effective moment of inertia. The values of $<D_{½+}>$ were taken from the work [10].

At low excitation energy the spin cut-off parameter and effective moment of inertia were determined from the approximation of the experimental spin distribution of well-known low-lying states by the statistical distribution (2). For ^{165}Er and ^{181}W the experimental infomation on spin of levels is reliable up to excitation energy of 0.384 MeV and 0.675 MeV, respectively [11]. The spin distributions for different values of ratio I_{eff}/I_{rig} are shown in fig.3.

RESULTS

The obtained data on absolute value of the nuclear level density and its energy dependence for ^{165}Er and ^{181}W are in a good agreement with the calculations on generalized superfluid model of nucleus with parameters presented in table 1 and with low-lying level data (see figs.1,2).

Table 1. Nuclear level density parameters

Parameter *Nucleus*	$\tilde{a}$, MeV^{-1}	Δ_o, MeV	δW, MeV	γ, MeV^{-1}	β	C_v, MeV^{-1}	ω_{2+}, MeV	ω_{3-}, MeV
^{165}Er	*15.4*	*1.04*	*-0.17*	*0.073*	*0.300*	*0.030*	*0.5*	*1.0*
^{181}W	*18.0*	*1.03*	*-2.87*	*0.075*	*0.253*	*0.025*	*0.6*	*1.0*

However, more detailed presentation of data as ratio of experimental and calculated results (fig.2^b) displays the steplike structure in the energy dependence of the derived level density of ^{165}Er. Similar structure in energy dependence of level density was predicted in model calculations taking into account the pairing correlations at fixed number of excited quasiparticles [1] and is connected with new quasiparticles states at break of each additional pair. As one can see in fig.2^b the most pronounced enhancement of level density begins at excitation energy of about 2 MeV. It corresponds the doubled value of correlation function for ^{165}Er ($2\Delta_0$) – the quantity determined the thresholds of n –quasiparticles excitations. The next enhancement of level density is observed at excitation energy slightly higher of 4 MeV and corresponds to the next threshold of quasiparticle excitations.

The values of spin cut-off parameter and ratio of Ieff / Irig determined according to the described procedure are presented in table 2.

Table 2. Deduced spin cut-off parameter σ and effective moment of inertia I_{eff}.

Parameter *Nucleus*	*U,* *MeV*	σ	I_{eff}/I_{rig}, (r_o = 1.25 fm)
^{165}Er	*6.66*	*6.3±1.2*	*0.81±0.34*
	0.19	*3.0±0.3*	*1.1±0.2*
^{181}W	*6.65*	*6.2±0.7*	*0.72±0.29*
	0.34	*3.5±0.3*	*1.0±0.2*

The obtained data for both nuclei are in an agreement in the limits of errors with their rigid body values. In the model of the non-interacting fermions the effective moment of inertia is equal to a rigid body value with mass and radius of the nucleus. In the superfluid model of nucleus it is so only at excitation energy higher than the critical energy of the phase transition to superfluid state, and lower than the critical energy the effective moment of inertia decreases rather essentially. In fig.4 the results of the moment of inertia energy dependence model calculations are presented. The comparison of data obtained by us with model predictions shows that energy dependence of the effective moment of inertia for both nuclei is in agreement with model of non-interacting fermions. It can be seen from fig.4 also that the values of effective moment of inertia for ^{181}W obtained in the present work do not confirm the results of work [3] determined from the measurements and analysis of neutron angular distributions in reaction $^{181}Ta(p,n)^{181}W$.

CONCLUSION

The absolute value, energy and spin dependences of the nuclear level density for nuclei of ^{165}Er and ^{181}W have been determined from analysis of the experimental data on neutron emission spectra in (p,n) reaction, the average S-wave neutron resonance spacing and spin distributions of low-lying states. The energy dependence of nuclear level density is in a good agreement with calculation on generalized superfluid model of nucleus and with low-lying level data. For ^{165}Er the steplike structure in the energy dependence conditioned by interacting via a pairing force is observed. It is confirmed the rigid body value of effective moment of inertia, was called in question for heavy nuclei in a number of experimental works [3,12,13,14].

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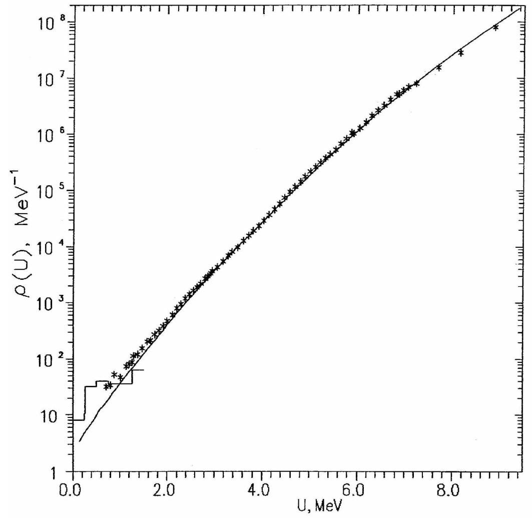


Fig.1. Nuclear level density of ^{181}W. The symbols indicate the experimental data, the curve – the result calculated on generalized superfluid model of nucleus, the histogram – the density of low-lying levels.

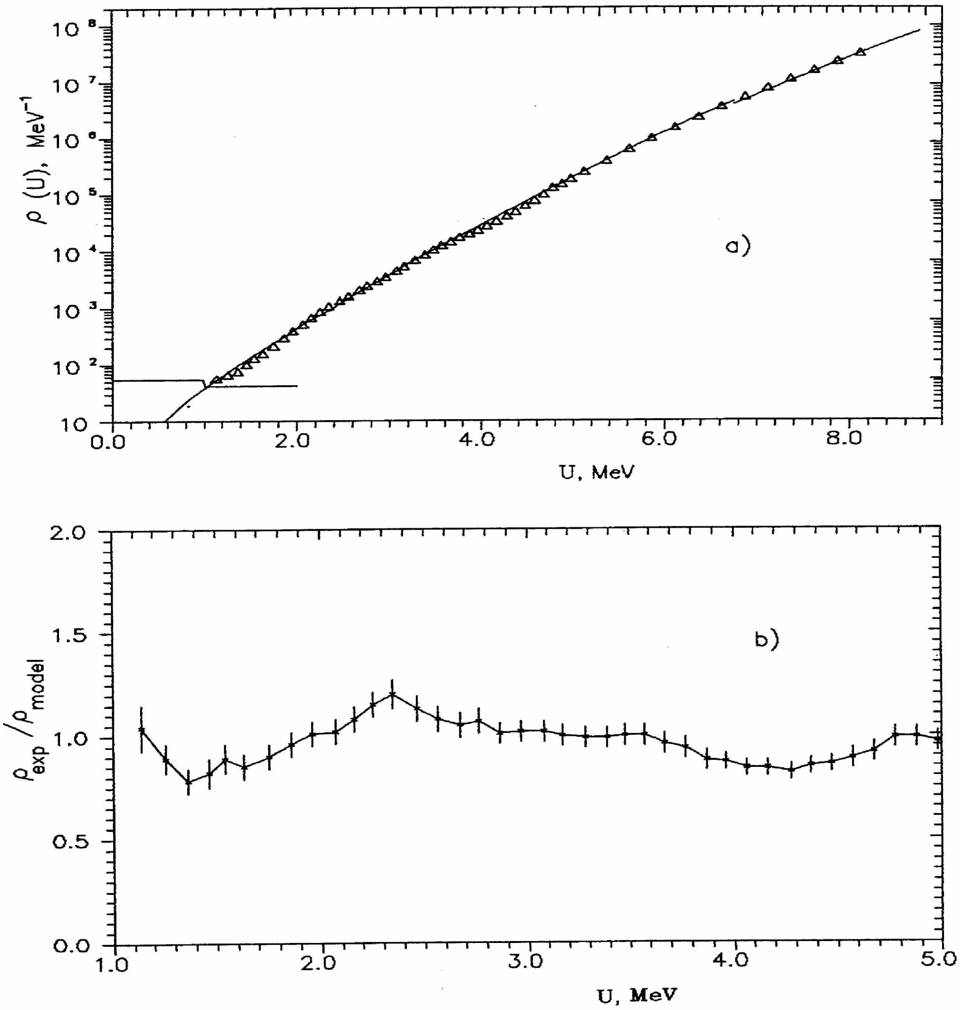
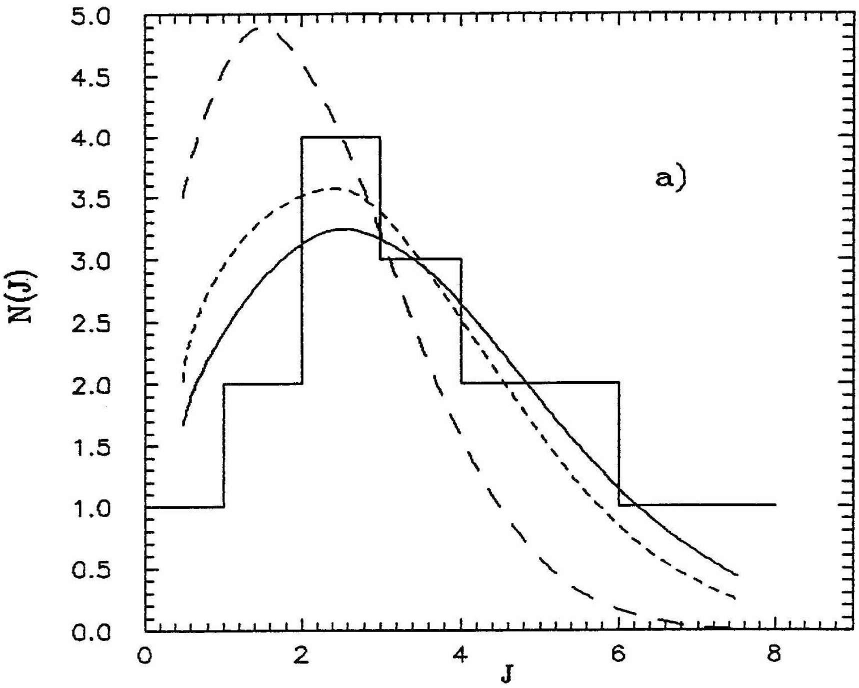


Fig. 2 a) Nuclear level density of ^{165}Er : the symbols indicate the experimental data from analysis of evaporation spectra, the histogram – the density of low-lying levels, the curve – result calculated on generalized superfluid model of nucleus, b) Ratio of experimental and calculated nuclear level densities.



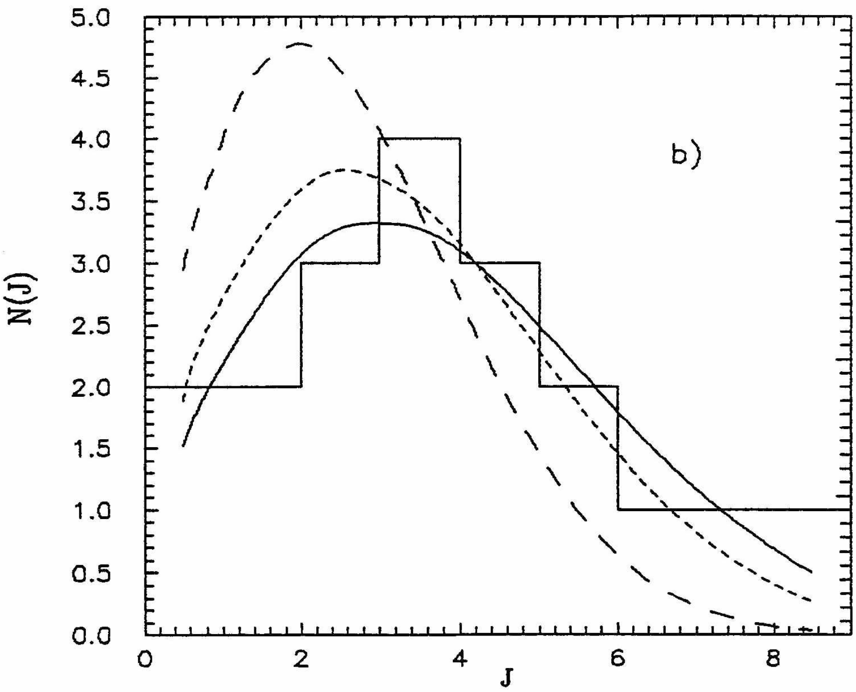


Fig. 3 The spin distribution of low-lying states. The histograms are experimental data, the curves are the description by the statistical distribution (1) for different values of I_{eff}/I_{rig}: a)^{165}Er: the solid line corresponds to ratio $I_{eff}/I_{rig}=1.1$; the short dashed – 0.9; the long dashed – 0.5, b)^{181}W: the solid line – $I_{eff}/I_{rig}=1.0$; the short dashed – 0.8 ; the long dashed – 0.5 .

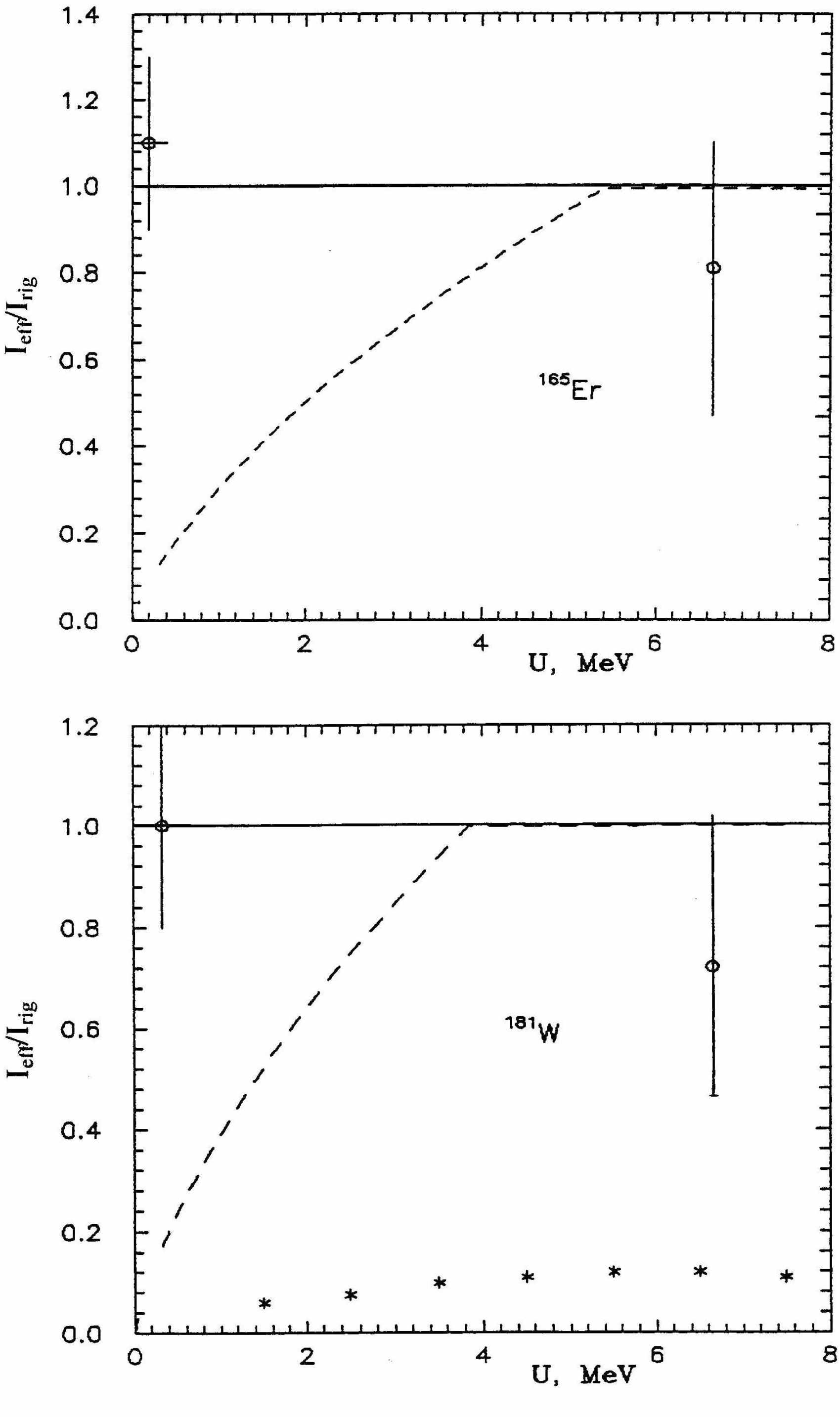


Fig. 4 Energy dependence of the effective moment of inertia. o simbols denote our data, * - data of work [2], solid line indicates the moment of inertia predicted in the model of non-interacting fermions, dashed line – in the superfluid model of nucleus.