MODEL-FREE DETERMINATION OF LEVEL DENSITY, RADIATIVE STRENGTH FUNCTIONS AND GENERAL TENDENCY NUCLEAR STRUCTURE CHANGING BELOW B_n

V.A.Khitrov, A.M.Sukhovoj

Laboratory of Neutron Physics, Dubna, Russia, 141980

The chief goal of experimental and theoretical investigations in low energy nuclear physics is the creation of a consistent model representation of the properties of nuclei in a specified interval of their excitation energy. In practice, it is necessary that the density ρ of the excited levels of nuclei in a specified interval of their quantum numbers together with the radiative strength functions k should be determined. Unfortunately, experimentalists have not been able to find a universal precise solution to the problem so far.

The new information about ρ and k appeared after the procedures for the determination of the intensities of two-step cascades as a function of the energy of their primary gamma-transition [1]:

$$I_{\gamma\gamma} = \sum_{\lambda,f}\sum_{i} \frac{\Gamma_{\lambda i}}{\Gamma_{\lambda}}\frac{\Gamma_{if}}{\Gamma_{i}} = \sum_{\lambda,f} \frac{\Gamma_{\lambda i}}{< \Gamma_{\lambda i} > m_{\lambda i}} n_{\lambda i} \frac{\Gamma_{if}}{< \Gamma_{if} > m_{if}}, \quad (1)$$

connecting the neutron resonance and specified low-lying levels of the studied nucleus and those for the extraction [2] from the data on the density of levels ρ and radiative strength functions

$$k = \Gamma_{\lambda i}/(E_{\gamma}^3 \times A^{2/3} \times D_{\lambda}) \quad (2)$$

of cascade gamma-transitions, were developed.

A quite essential regularly observed difference between the observed and the calculated for 51 investigated up to now nuclei distributions of cascade intensity with the total energy $E_1 + E_2 = B_n - E_f$ (if the energies of their final level $E_f < 1$ MeV) shows that the existing representations and models of cascade gamma-decay need in serious correction.

From analysis of ρ and k yielded by studies of two-step cascades it follows that the structure of the wave functions of the excited levels is essentially different for their energy regions below and above $\sim 0.5B_n$. Consequently, the level density and the probability of their population (depopulation) differ significantly from those predicted on the basis of model representation of the nucleus as a purely fermion system (for example,[3,4]).

The specific character of the data obtained in [2] together with analysis of the conditions of the corresponding experiment calls for going over not only to more realistic models of level density ρ and radiative strength functions (2) (in a manner that would maximally reduce their dependence on the mass of the nucleus A) (of the type [5,6] and [3,7], respectively), but also to their more precise parameterization and further development.

Unfortunately, however, ρ and k obtained in accordance with [2] contain some unknown systematic error whose ordinary part is determined mainly by the inaccuracies of $I_{\gamma\gamma}$

determination. But in the present-day experiment it can be easily minimized to the small enough level not exceeding 5-20%.

In the present stage of technique development [2], the specific part of the systematic error is determined by possible existence of dependence of the strength function not only on the energy E_γ of a specified multipolarity quantum but also on the excitation energy E_{ex} of the decaying level , not accounted for in [2], i.e., by the existence of the function $k = F(E_\gamma, E_{ex})$ in place of the assumption that $\Gamma_{if}/\Gamma_i = F(E_\gamma)$ made when Eq. (1) was derived.

But we found the possibility to estimate the effect of the decaying level energy E_{ex} on the relative value of the radiative strength functions of gamma-transitions of equal multipolarity and energy. For all the investigated nuclei there is obtained a considerable volume of information about the intensities

$$i_{\gamma\gamma} = i_1 \times i_2 / \sum i_2, \tag{3}$$

that are energy-resolved in the spectra as pairs of peaks of individual cascades. Their parameters, including the most probable quanta ordering, are reliably extracted from the experiment up to the cascade intermediate level excitation energy 3-5 MeV with the help of an original technique of analysis created in Dubna that employs a numerical algorithm of resolution improvement providing for a maximum possible resolution of all the obtained spectra $E_1 + E_2 = const$ without loss of effectiveness [8].

From Eq.(3), taking advantage of the presently available data on $i_{\gamma\gamma}$, i_1 and i_2 the total population $P = \sum i_2$ of about 100 levels can be determined for the majority of the above enumerated nuclei to their excitation energy 3-4 MeV and higher. The difference between P and the intensity i_1 of primary transitions to each of the levels is equal to the sum of their population by 2-, 3-, etc.-quantum cascades.

Since at present, there is practically no possibility to determine experimentally the population of all, without exception, intermediate levels of two-step cascades even at their moderate excitation energies (due to the existing threshold of registration of the intensities $i_{\gamma\gamma}$, i_1 and i_2), it is reasonable to perform an experiment to calculation comparison for $P - i_1$ summed over a small interval of excitation energies. Such sums should be looked at as a lower estimate for each of the intervals.

The general regularities of changes in the level population with their changing excitation energy can be understood in three variant of calculations:

(a) the density of levels is predicted by the model [4], the strength function of E1-transitions is specified by known extrapolations of the giant electric dipole resonance in the region below B_n, and $k(M1) = const$ is specified by the normalization of $k(M1)/k(E1)$ to the experiment around B_n;

(b) ρ and k, that are obtained in accordance with [2] and reproduce exactly the intensity of two-step cascades as a function of energy of their primary transition, are used (at present, only for the final levels in the cascades with $E_f < 1$ MeV);

(c) a set of level density and strength function values is chosen to reproduce exactly ($\chi^2/f << 1$) the values of $I_{\gamma\gamma} = F(E_1)$, the total radiative width Γ_γ of the decaying compound state and the values of $P - i_1$ at the same time.

The realization of the variant (c) is possible in the iteration mode: for k obtained in accordance with [2] there is selected some dependence function that would change the secondary gamma-transition strength function values with respect to that of the strength function obtained in accordance with [2] to enable the best reproduction of $P - i_1$. To this end, it suffices to multiply the strength functions of the secondary gamma-transitions to the levels below some boundary excitation energy U_2^{max} by the function h containing several narrow peaks. The dependence of their behavior on the excitation energy of the nucleus can be determined by analogy with the specific heat of ideal macrosystems in the second-order phase transition point as:

$$h = 1 + \alpha \times (ln(|U_c - U_1|) - ln(|U_c - U|)) \quad if \quad U < U_c, \tag{4}$$

$$h = 1 + \alpha \times (ln(|U_c - U_2|) - ln(|U_c - U|)) \quad if \quad U > U_c, \tag{5}$$

with some parameters $\alpha,\ U_1,\ U_2\ U_c$.

In the best variant tested by us, the amplitude α must grow from zero (linearly, for example) up to the maximally possible value shown in [9] as the excitation energy U decreases from $U = B_n$. The positions of the peaks, their amplitude and form are determined quite unambiguously by $P - i_1$. The population of any level whose number is l is determined by the equation:

$$P_l = \sum_m P_m \times \Gamma_{m,l}/\Gamma_m, \tag{6}$$

that depends on the population of all m higher-lying levels and on the branching coefficient of their decay. Although the data on the population depend on the two factors in the equation, the value of P for the different low-lying levels is mainly determined by the relationship between the partial widths of the secondary transitions populating them. Eq. (6) gives no other possibility to ensure an essential increase in the population of higher-lying levels.

The determined correcting functions are then included in the analysis [2] for the determination of ρ and k that exactly reproduce the cascade intensities taking into account an assumed difference between the energy dependence of the strength functions of the primary and secondary transitions in the cascade. If necessary, the cycle is repeated once at most if the hypothesis of linearly growing distortions in the value of $k(E1)$ and $k(M1)$ with increasing energy of the decaying levels is used and several times if the hypothesis of $\alpha = const$ is employed.

The effects of the different distorting factors for obtaines ρ and k for all set of investigated nuclei can be partially reduced by averaging them separately over even-even, even-odd and odd-odd compound nuclei. In the suggested variant, B_n equals unity for each of the nuclei and the level density is taken in the form of its relationship with the simplest interpolating function $const \times exp(\kappa E_{ex})$, whose parameters are fully determined by the densities of neutron resonances and levels in the excitation energy region around 1-2 MeV. Since k presented by (2) depends weakly on the mass of the nucleus, the sum of the strength functions of dipole transitions is directly averaged over nuclei with equal

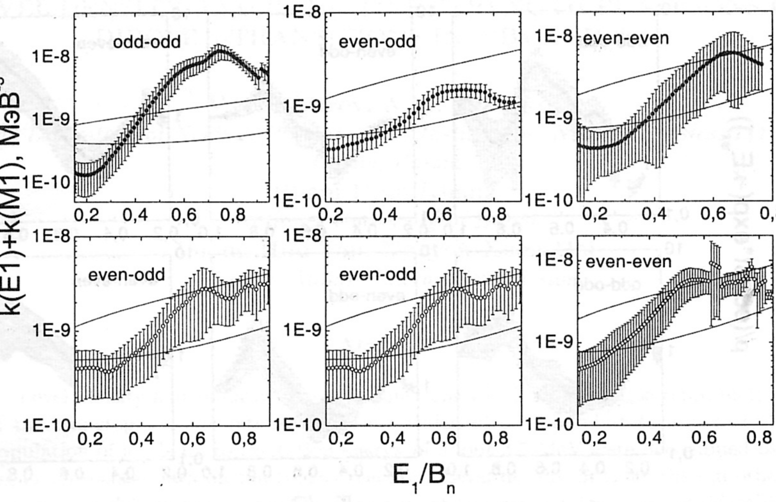

Fig. 1. *A comparison of the mean sums of the radiative strength functions of nuclei with the different parity of the number of neutrons and protons. Dark circles with errors - only nuclei for which the level population is determined. Open circles - all the nuclei for which the analysis [2] is performed without accounting for the difference between the energy dependence of the strength functions of the primary and secondary transitions. Upper curve - predicted by the model [10], lower curve -[3] under the assumption that* $k(M1) = const$

parity of nucleons. The averaging is performed for a set of a larger part of 40 nuclei for which ρ and k are determined by the method [4] as well as for the nuclei whose population of individual levels is determined. As it is seen from Fig.1, in the first and the second variants the energy dependence $k(E1) + k(M1) \approx const$ for the primary transitions with $E_1 < 0.3B_n$ independently on the nucleus type. This confirms the principal validity of the basic representations of the model [3] for gamma-transitions from the compound states to the high-lying levels. Maximal possible values of $k(E1)+k(M1)$ are observed in the region $E_1 \approx (0.7 - 0.8)B_n$ and they decrease as the primary transition energy further increases. As it is seen from Fig. 2, the function $R = const \times \rho \times exp(-\kappa E_{ex})$ has step-like structure with extremes in the region of $E_{ex} \sim 0.2$ and $\sim 0.8B_n$ and a minimum at about $0.5B_n$.

The attribute of the second-order phase transition is a sharp change in the internal properties of the investigated system as its energy changes. While quite a sharp change in the level density (i.e., in the specific heat of the nucleus, in fact) was earlier established experimentally in [2] with a sufficiently high reliability, the results of the performed analysis point to a sharp change in the reduced probability of gamma-transitions (primary, at least) in some, rather narrow, region of the levels of any nucleus excited by them.

The above reported results, that point to an essential increase in the radiative strength functions of secondary gamma-transitions for practically the same region of energies, can be considered as an additional independent proof of the existence of some region of excitation energies in the nucleus where a sharp change in the structure of the nucleus

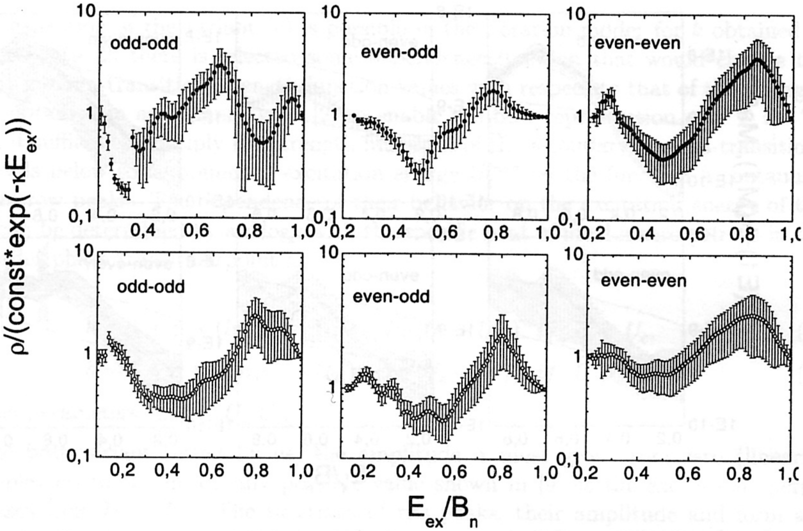

Fig. 2. *Mean relative variations of the level density. The notation is similar to Fig. 1.*

takes place. Presumably, it is a transition from domination of vibrational excitations to that of quasiparticle ones. Apparently, this can be interpreted as a phase transition from superfluid to ordinary state of such a specific system as nucleus. The effect is possibly associated with a breakup of the only pair of nucleons at excitation energies corresponding to a sharp decrease in the level density.

References

1. S. T. Boneva, V.A. Khitrov, A.M. Sukhovoj, *Nucl. Phys.* **A589**, 293 (1995).
2. E.V. Vasilieva, A.M. Sukhovoj, V.A. Khitrov, *Phys. At. Nucl.* **64(2)**, 153 (2001). E.V. Vasilieva, A.M. Sukhovoj, V.A. Khitrov, *INDC(CCP)*, Vienna, **435**, 21 (2002)
   http://arXiv.org/abs/nucl-ex/0110017
3. S.G. Kadmenskij, V.P. Markushev, W.I. Furman, *Sov. J. Nucl. Phys.* **37**, 165 (1983).
4. W. Dilg, W. Schantl, H. Vonach, M. Uhl, *Nucl. Phys.*, **A217**, (1973), 269.
5. E.M. Rastopchin, M.I. Sviron, G.N. Smirenkin, *Jad.Fiz.*, **52**, 1258 (1990).
6. A.V. Ignatiuk, Yu.V. Sokolov, *Jad.Fiz.*, **19**, 1229 (1974).
7. V. A. Plujko, *Nucl. Phys.*, **A649**, 209 (1999).
   http://www-nds.iaea.or.at/ripl2/
8. A.M. Sukhovoj, V.A. Khitrov, *Instrum. Exp. Tech.*, **27** (1984) 1071
9. http://arXiv.org/abs/nucl-ex/0406030
   http://arXiv.org/abs/nucl-ex/0410015
10. P. Axel, *Phys. Rev.*, **126(2)**, 671 (1962).