объединенный
институт
ядерных
исследований
дубна

E15-93-370

N.P.Balabanov*, A.G.Belov, Yu.P.Gangrsky,
F.G.Kondev, A.P.Tonchev

EXCITATION OF THE HIGH-SPIN ISOMERS ^{180m}Hf, ^{190m}Os AND ^{204m}Pb IN (γ, γ') REACTIONS

Submitted to «Zeitschrift für Physik A»

*Department of Nuclear Physics, Plovdiv University,
4000 Plovdiv, Bulgaria

1993

I. Introduction

In the even-even nuclei there are observed high-spin isomers with spins up to $30\hbar$ and half-lives up to several years [1]. Usually investigations of these isomers have been performed in reaction induced by protons, α-particles and heavy ions but their investigation in (γ,γ') reactions, however, is of great interest. Firstly, since there are not Coulomb barrier and binding energy for γ-quanta, one can obtain excited nuclei both in the region above nucleon threshold and below it. Secondly, the momentum being introduced into nucleus by γ-quantum is not varied with energy increase (it is $1\hbar$ at dipole absorption and $2\hbar$ at quadruple one). Therefore, for an even-even nucleus the spin and parity of the initial compound states are unambiguously determined (1^-, 1^+ or 2^+) and γ-quanta cascade leads to an isomeric state.

In the present work there have been investigated (γ,γ') reactions producing high-spin isomers of nuclei belonging to three different regions: strongly deformed (^{180}Hf), transitional (^{190}Os) and spherical (^{204}Pb). The experimental isomeric ratios have been compared with statistical model calculations and parameters describing γ-cascades have been obtained.

II. Experimental method

The present investigations have been carried out on the beam of bremsstrahlung gamma quanta of the microtron MT-25 FLNR, JINR, Dubna in the energy region from 6 to 15 MeV. The electron beam extracted from the accelerator microtron chamber was directed on a tungsten stopping target by means of a system of quadruple lenses. The target thickness was 2 mm and just behind it a 30 mm aluminum absorber was placed. The mean electron current on the target (8-10 μA) was measured continuously during the experiments. The electron energy was determined through measurements of the guiding microtron magnetic field using the nuclear magnetic resonance method.

Samples of enriched isotopes ^{180}Hf(99.3%), ^{190}Os(78.5%) and ^{204}Pb (99.7%) were picked up in aluminum foil and during irradiation were placed just behind the aluminum absorber. Irradiation time $t_{irr.}$ was varied for different targets ($t_{irr.} \leq 3T_{1/2}$ -where $T_{1/2}$ is the half-life of isomers). Natural abundance indium monitors 50 μm thick were placed just in front of the targets.

The investigation of the isomeric states population was performed using activation technique. The lines corresponding to the γ-cascades of the isomers were registered by a Ge(Li) detector (with 60 cm^3 volume and energy resolution ΔE=3.5 KeV for E_γ=1332 KeV ^{60}Co) coupled to a 4096-multichannel analyzer. The detector efficiency was experimentally determined using the OSGI standard sources [2]. The γ-spectra were processed by means of the SPM-program [3]. The spectroscopic characteristics of the isomeric states and the recorded spectra are shown in Table 1. and Fig. 1. respectively.

Table 1. Spectroscopic characteristics of the investigations isomers

NUCLEUS	HALF-LIFE	J^π	$E_{\gamma1}$ KeV	$I_{\gamma1}$ %	$E_{\gamma2}$ KeV	$I_{\gamma2}$ %	$E_{\gamma3}$ KeV	$I_{\gamma3}$ %	REF.
^{180m}Hf	5.5 h	8^-	215.3	75	332.3	94	443.2	76	[3]
^{190m}Os	9.9 m	10^-	186.7	70	361.2	95	502.5	98	[4]
^{204m}Pb	67.2 m	9^-	374.7	90	899.2	99	911.7	99	[5]

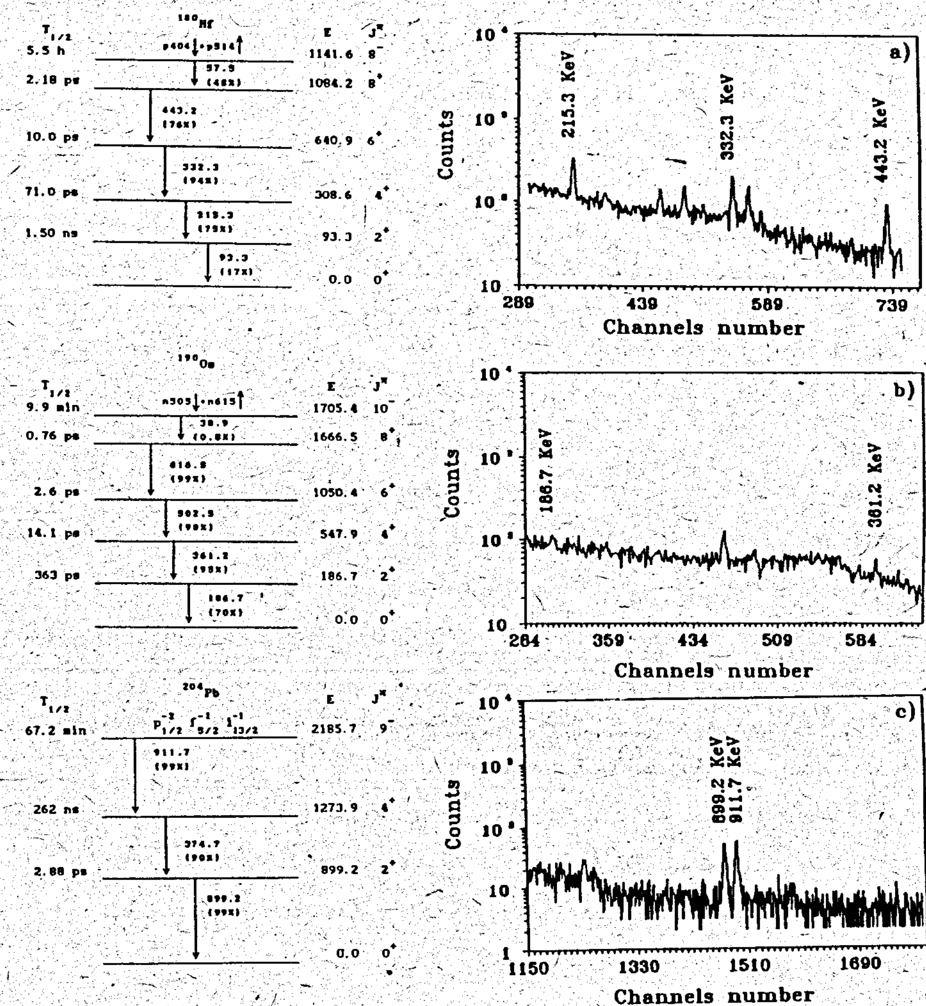

Fig. 1. Decay scheme and obtained γ-ray spectra for investigated nuclei: a) ^{180}Hf(γ,γ')^{180m}Hf; b) ^{190}Os(γ,γ')^{190m}Os; c) ^{204}Pb(γ,γ')^{204m}Pb.

III. Experimental results

The yields $Y(E_{\gamma max})$ of the reactions (γ,γ') were obtained by means of the relative method comparing the γ-ray photo-peak areas of the isomers and the one of the γ-line E_γ=336 KeV of ^{115m}In:

$$Y(E_{\gamma max}) = \kappa\, Y^m(E_{\gamma max}) \qquad (1)$$

$$\kappa = \frac{n^m\, \lambda\, S\, \varepsilon^m_D\, I^m_\gamma\, f^m(t_{irr}, t_{col}, t_m)}{n\, \lambda^m\, S^m\, \varepsilon_D\, I_\gamma\, f(t_{irr}, t_{col}, t_m)} \qquad (2)$$

where n-number of nuclei; S-photo-peak area; ε_D-detector efficiency I_γ-γ-line intensity; $f(t_{irr}, t_{col}, t_m) = (1-e^{-\lambda t_{irr}})e^{-\lambda t_{col}}(1-e^{-\lambda t_m})$; t_{irr}, t_{col}, t_m - time of irradiation, cooling and measuring; λ-decay constant. Index m relates to the monitor reaction $^{115}In(\gamma,\gamma')$ which yield was determined by integration of its excitation function:

$$Y^m(E_{\gamma max}) = \int_0^{E_{\gamma max}} \sigma^m(E_\gamma)\, F(E_\gamma, E_{\gamma max})\, dE_\gamma \qquad (3)$$

where $\sigma^m(E_\gamma)$-(γ,γ') reaction cross-sections [4]; $F(E_\gamma, E_{\gamma max})$-energetic dependence of the bremsstrahlung spectrum [5].

During the irradiations besides bremsstrahlung γ-quanta neutrons (emitted from the stopping target and the lead protection around it) reach the samples. Therefore, much attention has been paid to account for the contribution of (n,γ) and (n,n') reactions to the production of the investigated isomers. The (n,γ) reaction leads to ^{180m}Hf isomers production from ^{179}Hf nuclei ($J^\pi_0=9/2^+$, with 3.1% abundance in the target and cross-section $\sigma^m_{(n,\gamma)}$=0.34±0.03 b [6]) and ^{190m}Os from ^{189}Os ($J^\pi_0=3/2^-$, with 7% abundance in the target and cross-section $\sigma^m_{(n,\gamma)}=(2.6\pm0.3)10^{-4}$ b [6]). Measuring the flux of thermal neutrons with the help of the monitoring reaction $^{115}In(n,\gamma)^{116m}In$, the contribution of the (n,γ) reaction to the production of ^{180m}Hf was not more than 5% and less than 1% for ^{190m}Os.

The influence of fast neutron in (2) was computed using the expression:

$$S^{(n,n')} = n\varepsilon_D I_\gamma f(t_{irr}, t_{col}, t_m)\Omega I_o Y_n \int_0^{E_{nmax}} \sigma^{(n,n')}(E_n) N(E_n, E_{nmax}) dE_n \qquad (4)$$

where I_o-number of electrons reaching the bremsstrahlung target; Y_n-neutrons yield per one electron [7]; $\sigma^{(n,n')}(E_n)$-(n,n') reaction cross-section [8,9,10]; $N(E_n, E_{nmax})$-normalized neutron spectrum distributions [11]; E_{nmax}-maximum neutron energy; Ω-geometrical factor. Our calculations show that at electron energies below 9 MeV the influence of fast neutrons for all the investigated nuclei is less than 1%. With energy increase up to 15 MeV, however, it increases up to 15-20%.

The accuracy of the yields depends on uncertainties in the determination of photo-peak areas. It depends mainly on the quantity of investigated nuclei in the target, the conditions of the irradiation, cooling and measuring times, end-point energy of the bremsstrahlung spectrum and neutron contribution to isomer productions. It was about 5-30% for ^{180m}Hf and ^{204m}Pb and 15-60% for ^{190m}Os. From the obtained yields the cross-sections have been restored by method of minimization of the directioned discrepancy [12]. In Fig.2 and Fig.3 there are shown the experimental cross-sections-σ^m and isomeric ratios $\eta=\sigma^m/\sigma^{tot.}$ ($\sigma^{tot.}$-total photo-absorption cross-section) versus γ-quanta energy. The errors in cross-section values have been determined by the error limits after multiple cross-sections restoration with the random variation of initial data distributed by the Poisons law.

The cross-sections of the investigated reactions have a resonance

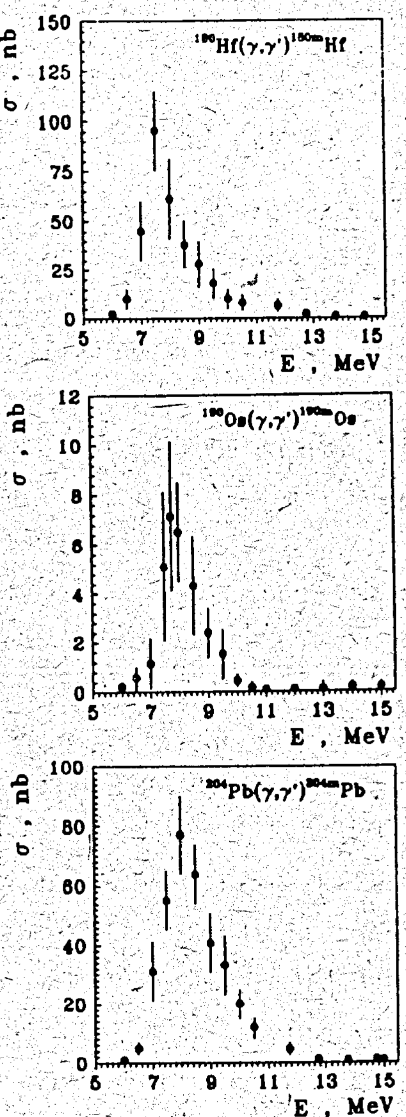

Fig.2. Excitation functions of the investigated reactions.

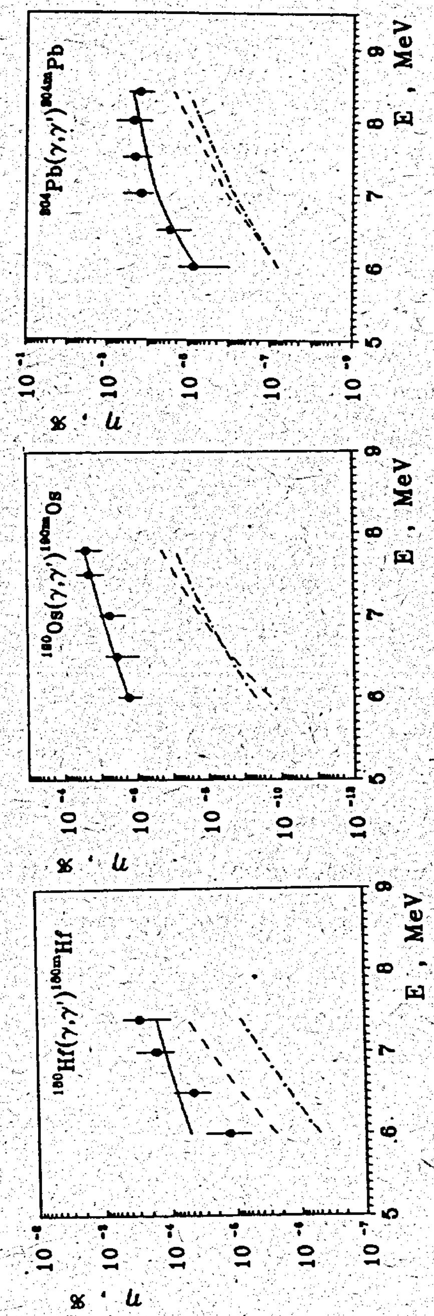

Fig.3. Isomeric ratios η of the investigated reactions as a function of γ-quanta energy; ─●─ -experimental data; ──── -calculation with taking account of the nature of initial and final states; -·-·- -calculation with RSF on the giant resonance model; - - - -calculation with RSF on the constant values.

shape and their maxima within the accuracy of the measurements coincide with the threshold of (γ,n)-B_n reaction. The sharp cross-section decrease at energies above B_n is connected with the competition of neutron channel ($\Gamma_n \gg \Gamma_\gamma$) which at $E_\gamma \geq 9$ MeV turns out to be observable and leads to significant decrease of total cross-sections of (γ,γ') reactions.

IV. Theory and results

Statistical model calculations for the cross-sections of the investigated reactions in the energy range 6-9 MeV have been performed. The following assumptions were made:

1) After the absorption of a γ-quantum with energy E_γ and multipole order XL=E1,M1 and E2 by a even-even nucleus there are formed initial compound states with well defined characteristics: $E^*=E_\gamma$, $J^\pi=1^-$, 1^+ and 2^+.

2) The compound-nucleus is deexcited by means of γ-quanta cascade of multipole order E1, M1 and E2.

3) The population of low-energy nuclei states (including isomeric ones) depends on γ-quantum energy, characteristics of the initial and final states and also on the spin and energy dependence of level density.

The photo-absorption cross-section for a γ-quantum energy E_γ is given by [13]:

$$\sigma(E^*,J^\pi) = (\pi\lambda^2) g_J \frac{\Gamma^{XL}_{J_oJ}}{D_J} \omega_\pi \qquad (5)$$

where λ-photon wavelength, g_J-statistical weighting factor, D_J-spacing between compound-nucleus levels, $\Gamma^{XL}_{J_oJ}$-partial transitation width between levels with spins J_o (ground) and J (compound),

$\omega_\pi = \dfrac{1-(-1)^L \pi_o \pi}{2}$, XL-parity and multipolarity of the γ-quantum.

The gamma ray cascade and the population of low levels (E^*_f, J_f, π_f) have been calculated using the algoritm described in [14]. The probability of a radiative transition from a nuclear state i (E^*_i, J_i, π_i) to a state f is given by:

$$dW_{if} = \frac{\Gamma_{if}}{\Gamma^i_{tot}} \rho(E^*_f, J_f^{\pi_f}) dE_f \qquad (6)$$

where Γ_{if} and $\Gamma^i_{tot} = \sum_f \Gamma_{if}$ are the partial and the total widths of the initial state, $\rho(E^*_f, J_f^{\pi_f})$-level density for the final state.

The characteristics of the levels in the lowest excitation energy region $E^* \leq E^*_{cut}$ (E^*_{cut}-excitation energy of the last known low-lying level) are taken from [15,16,17]:

$$\rho(E^*,J^\pi) = \sum_{f=1}^{N} \delta(E^*-E^*_f)\delta_{JJ_f}\delta_{\pi\pi_f} \qquad (7)$$

where N is the number of the known low-lying levels.

The level densities for excitation energies $E^*>E^*_x$, have been obtained using the Fermi-gas model [18]:

$$\rho_H(E^*,J^\pi) = f(J)\frac{\exp\left[2(a(E^*-\Delta))^{1/2}\right]}{12(2)^{1/2}\sigma a^{1/4}(E^*-\Delta)^{5/4}} \qquad (8)$$

where E^*_x is the matching energy; a-level density parametr; Δ-pairing energy [19];

$$\sigma^2 = (6/\pi^2)0.146A^{2/3}\ (a(E^*-\Delta))^{1/2} \qquad (9)$$

spin cut-off parametr;

$$f(J) = \frac{(2J+1)}{2\sigma^2}\exp\left[-\frac{(J+1/2)^2}{2\sigma^2}\right] \qquad (10)$$

spin dependence of the level densities.

For excitation energies below E^*_x the level densities have been described by the constant tempetature model [18]:

$$\rho_L(E^*,J^\pi) = f(J)\frac{1}{T}\exp\left[(E^*-E_o)/T\right] \quad (11)$$

where E_o is a fitting parameter; T-nuclear temperature. In this region, the spin cut-off parameter σ has been determined by interpolation between the σ_D^2 value, evaluated from the spins J_i of N-low excited known levels:

$$\sigma_D^2 = \frac{1}{2N}\sum_{i=1}^{N}(J_i+1/2)^2 \quad (12)$$

and the σ^2 value from (9) at $E^*=E_X^*$:

$$\sigma^2(E^*) = \frac{\sigma^2(E_X^*)-\sigma_D^2}{E_X^*-E_{cut}^*}(E^*-E_{cut}^*)+\sigma_D^2 \quad (13)$$

The parameters used in the calculations were determined according to the methods applied by Reffo [20]. The values of the level-density parameter a follow from the overall systematics, obtained by fitting the resonance sequences of nuclei. The parameters E_X^*, T and E_o were extracted by fitting to the step-like dependence of the comulative number of known discrete levels and by matching the low-energy and high-energy level density formulae at E_X^*. The parameters adopted in the calculations are shown in table 2.

Table 2. Level density parameters for investigation nuclei adopted in the present calculations

NUCLEUS	a MeV	E_x^* MeV	Δ MeV	E_o MeV	T MeV
^{180}Hf	20.32	4.62	1.37	-0.1414	0.5148
^{190}Os	20.36	5.39	1.16	0.0966	0.5220
^{204}Pb	12.91	3.52	1.54	0.2440	0.6430

If one fixes level density phenomenologically according to the

parametrization (7-13), then the possibility to describe populated states quantitatively the adequancy of the accepted ratios between the radiative transitions. According to the assumed calculation scheme, γ-transitions can be divided into three classes: CC', CS' and SS' (where C and C' conditionally denote the initial and final highly-excited compound states respectively, and S and S'-initial and final simple low-excited states (see Fig.4). Gamma transitation probabilities of SS' type for all nuclei have been taken from spectroscopical data [15,16,17].For the descriptin of CC' and CS' transitions, radiative strength functions (RSF) are used:

$$S_{if}^{XL} = \frac{\Gamma_{if}^{XL}}{D_i E_\gamma^{2L+1}} \quad (14)$$

At the present there vas experimental data on RSF of CS'-type obtained from measurements of partial and total widths of neutron resonances [21], from measurements of continuous γ-spectra after capture of thermal and resonance neutrons [22], and also γ-ray spectra of $(d,p\gamma)$ [22] and $(n,\alpha\gamma)$ [23] reactions. On the basis of their analysis the RSF is described by a constant strength function model (model 1) [18,21,24]: $S_{CS'}^{E1}=4.10^{-9}A^{2/3}CE1\ MeV^{-3}$; $S_{CS'}^{M1}=2.10^{-8}CM1\ MeV^{-3}$ и $S_{CS'}^{E2}= 3.5410^{-14}A^{4/3}CE2\ MeV^{-5}$, where CE1, CM1 and CE2 are normalization constants; or by the giant resonance model (model 2) [13,18,25]:

$$S_{CS'}^{E1} = \frac{\sigma_{tot}^D(E_\gamma)}{3(\pi\hbar c)^2 E_\gamma},\ MeV^{-3} \quad (15)$$

$$S_{CS'}^{E2} = \frac{1}{5(\pi\hbar c)^2 E_\gamma^3}\left[\sigma_{T=0}^Q(E_\gamma)+1.8\sigma_{T=1}^Q(E_\gamma)\right],\ MeV^{-5} \quad (16)$$

where $\sigma_{tot}^D(E_\gamma) = \sum_{J=1}^{N}\sigma_{mJ}\left[1+\left(E_\gamma^2-E_{mJ}^2\right)^2/\left(E_\gamma\Gamma_J\right)^2\right]^{-1}$, N=1 for spherical nuclei and N=2 for deformed ones; σ_{mJ}, E_{mJ} и Γ_J-are the parameters of the giant dipole resonance [26], and $\sigma_{T=0}^Q(E_\gamma)$ and $\sigma_{T=1}^Q(E_\gamma)$- total photoabsorption cross-sections of isoscalar (T=0) and isovector (T=1) giant quadrupole resonance [25].

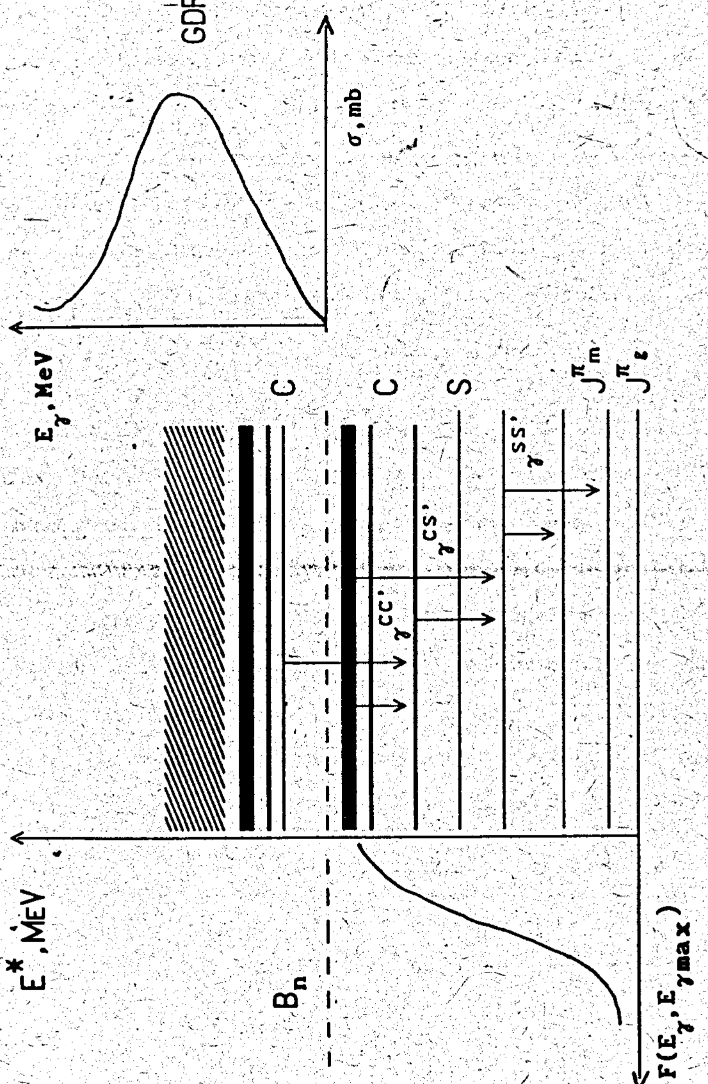

Fig.4. Calculation scheme of γ-quanta cascade.

Calculations for the investigated isomeric states populations (made with the use of both models for RSF and assumption about the indepedence of initial and final states $S_{CC'}(E_\gamma)=S_{CS'}(E_\gamma)$ [14]) are shown in Fig.3. As seen from the figure, theoretical calculations poorly agree with the experimental values and in most cases the coefficient of divergence is of one order. Even after reasonable variation of level density parametr a in (8) and spin cut-off parametr σ (9) one has succeeded in reproducing of only qualitative experimental results and at the same time quantatitative values are sensibly differed. Using experimental data about excitation functions of reactions (γ,γ') existing in literature for wide range of nuclei [27,28] for which difference of spins of the ground and isomeric states is relatively small (ΔJ=3-6) we have calculated cross-sections of these reactions using the both models for RSF. The obtained results show that isomeric ratios turn out to be less sensitive to different types of RSF and the both models well reproduce experimental results. As level density expotentially increases with excitation energy increase, then probability of populated levels with spin much more differed from spin of the ground state is mainly determined by the RSF compound-compound (C-C') γ-transitions ($E_\gamma \le 2$ MeV). On the one hand, the use of the model 1 for RSF with a normalization to experimental data of the C-S transitions leads to the increase of E1 part and decrease of E2-transitions part. On the other hand the use of the model 2 as showun in Fig.5 leads to the decrease of partial radiative widths Γ^{E1}_{if} и Γ^{E2}_{if} as $S^{E1(E2)}_{CC'}$ $E_\gamma(E^3_\gamma)$. However, as shown by theoretical estimates [31,32] and the known experimental data [23], RSF of $S^{E1}_{CC'}$ type practicaly do not depend on γ-quanta energy and $S^{E1}_{CC'} \approx S^{M1}_{CC'}$, and ratios of partial widths for M1 and E2 transitions $\Gamma^{M1}_{if}/\Gamma^{E2}_{if} \approx 10$. In view of this, we have computed population taking account of diferent nature of initial and final states ($S^{E1(E2)}_{cc'} \neq S^{E1(E2)}_{cs'}$). Ther has been used a systematics of experimental data [21] for $RSFS^{M1}$ and $S^{M1}_{cc'} = S^{M1}_{cs'}$. The model of giant resonances has been used for RSF C-S transitions $S^{E1(E2)}_{cs'}$. RSF of E1 compound-compound transitions ($E_{\gamma} \leq 2$ MeV) has been determined from the ratio $S^{E1}_{cc'} = S^{M1}_{cc'}$, and RSF $S^{E2}_{cc'}$ from the condition $\Gamma^{M1}_{if}/\Gamma^{E2}_{if} \approx 10$. The obtained results show a satisfactory agreement between calculation and experimental results, at the same time there is no need to introduce any free parameters.

V. Conclusion

In the present work there have been measured excitation functions of high-spins isomers in reactions (γ,γ') which have close relationship with some aspects of nuclear processes: the behaviour of total photoabsorption cross-sections below photonucleon threshold; the multiplisity and multipolarity of cascade γ-quanta; mechamism of photoabsorption. The preformed calculations showed that in γ-cascade besides electrical dipole transitions one should take into account the magnetic dipole and electric quadrupole transitions. Moreover, at population of high-spin isomers the primari soft γ-quanta running between compound-compound states play an important role that allows one in a new way to consider a problem of initial steps of intranuclear cascade connected with γ-decay of compound states.

There is small difference for the isomeric ratios in the spherical (^{204}Pb) and deformed (^{180}Hf) nuclei.

The Authors would like to thank Prof. Yu. Ts. Oganessian and Prof. Yu. E. Penionzhkevich for their support and interest in this work, and also Prof. B. I. Pustylnik for the critical remarks and helpful discussions.

References

1. Belenky V.M. and Grigoriev E.P.: Structure of even nuclei. Moscow: Energoatomizdat 1987
2. Vylov Ts. et al.: Joint Institute for Nuclear Research Preprint P6-9073, Dubna(1975)
3. Zhuchko V.E. In Workshop on "Modern directions in activation analysis at the JINR", D14-88-833, JINR, Dubna(1988)
4. Dzilavjan L et al., Preprint P-0473 INR Academy of Science USSR, (1986)
5. Kondev Ph., Tonchev A., Khristov Kh. and Zhuchko V.: Nucl. Instr. and Meth. **B71**.126(1992)
6. Grintakis E., Cullen D and Mundy G. :Handbook on Nuclear Activation Data № 273. IAEA.Vienna. 1987
7. Kovalev V. :Secondary emission of electron accelerators. Moscow. Atomizdat. 1979.
8. Vorotnikov P. et al. Neutron physics, T.3., c.208., Moscow. 1984
9. Decowski P., Grochulski W., Karolyi J., Marcinkowski A., Piotrovski J., Saad E. and Wilhelmi Z. :Nucl. Phys. **A204**. 121(1973)
10. Herman M. et. al. :Nucl. Phys. **A297**.335(1978)
11. Stavinsky V and Shubin Yu. :Nuclear constants. pp.52. 26. Moscow: CSRI Atominform, 1977.
12. Zhuchko V. :Yad. Fiz. **25**.299(1977)
13. Axel P. :Phys. Rev. **126**.671(1962)
14. Points W.P. :Z. Phys. **197**.262(1966)
15. Browne E.: Nuclear Data Sheets 52.127(1987)
16. Singh B.: Nuclear Data Sheets **61**.243(1990)
17. Schmorak M.: Nuclear Data Sheets **50**.719(1987)
18. Ignatiuk A. :Statistical properties of excited nuclei. Moscow: Energoatomizdat 1983

19. Truran J. and Cameron A., in Proc. Intern. Conf.: Properties of nuclei far from the region of beta-stability, Leysin, CERN 70-30. v.1., p.275., 1970.

20. Reffo G., CNEN report RT/FI/78/11, Bologna, 1978.

21. McCullagh C., Stelts M. and Chiren E. :Phys. Rev C23.1394 (1981)

22. Bartholomew G., Earle E., Ferguson A., Knowles J. and Lone M. : Advances in Nuclear Physics. 7.229(1973)

23. Popov Yu. :Particles & Nuclei. 13.1165(1982)

24. Endt P.M. :Atomic data and nuclear data tables. 26.47(1981)

25. Prestwich W., Islam M. and Kennett T. :Z. Phys. A -Atoms and Nuclei 315.103(1984)

26. Detrich R. and Berman B. :Atomic data and nuclear data tables. 38 193(1988)

27. Bigan Z. и др., Preprint KINR-84-13, Kiev, 1984.

28. Mazur V. and Take A., Preprint KINR-81-40, Kiev, 1981.

29. Bigan Z., Mazur V., Sokoljuk I. and Sychev S., Preprint KINR-88-13, Kiev, 1988.

30. Dzjilavjan L., Kauz V., Furman V and Chuprikov A., Preprint JINR P4-89-320, Dubna, 1989.

31. Kadmensky S., Markushev V and Furman V. :Yad. Fiz. 31.1175(1980)

32. Viaziankin N. and Urin G. :Yad. Fiz. 54.1508(1991)

Received by Publishing Department on October 15, 1993.