

Parameters of Cascade Gamma-Decay ^{52}V and ^{64}Cu Compound-States

*Mangengo Lumengano*¹, *Pham Ding Khang*², *Hai Nguyen Xuan*², *Nguyen Ngoc Anh*²,
*A.M. Sukhovo*³

¹ Agostinho Neto University (Angola), ² Vietnam Atomic Energy Institute,
³ Joint Institute for Nuclear Research

Abstract

In this work, intensities of two-step gamma-cascades decay in compound nuclei ^{52}V and ^{64}Cu are measured. From their intensity distribution in function of the primary gamma-transition energy, are determined the most probable values of level density and the radiative strength function for $E1$ - and $M1$ -transitions. The results confirm the findings of the analysis of similar data for 40 nuclei, in the range of nuclear masses $40 \leq A \leq 200$, that values of level density and radiation strength function for ^{52}V and ^{64}Cu , like in any other nuclei, are determined by the number of pair-breaking nucleons.

Introduction

The density ρ of the excited levels and the partial width Γ of the emission product of level i at nuclear reaction excitation energy E_i are determined by the number of unpaired quasi-particles nucleons and by any number of phonon excitations. That conclusion is quite clear and follows from the results of the model describing the intensity of two-step gamma-cascades between the initial λ and the final f levels [1,2]. The possibility for Cooper pairs breaking to occur needs at least about two pairing energy, $2\delta_0$, for the last nucleon. This energy varies for different pairs of given nucleons. The last conclusion follows from the available data on masses of nuclei (see for example [3]).

Therefore, values of ρ and Γ for any nucleus at any excitation energy are random functions with finite range of their fluctuations. It is not excluded, additionally, that they are also directly dependent on the number of nucleons in a given shell and on the deformation of nuclei, etc. [4]. Therefore, for the development of new practical models for the calculation of level densities, gamma-ray strength functions, and nuclear reaction cross sections, it is necessary to study the two-step gamma-cascades from thermal neutron capture reactions in a wide range of nuclear target mass. More broadly, for the understanding of nuclear properties, it is also necessary to study gamma-cascades transitions, the first step of which is the evaporated nucleons.

Experiment

The targets of Vanadium and Copper with natural abundance were placed between two HPGe detectors. Experimental data on gamma-gamma coincidences were collected for about 280 hours for Vanadium target and 600 hours for Copper target. The experimental system has been installed at the tangential beam port of the DNRR.

The thermal neutron beam was filtered by S, Pb and Si. The neutron flux has the cadmium ratio of 900 and the neutron beam at the target position was $1.02 \times 10^6 \text{ n/cm}^2\text{s}^{-1}$. The

beam collimator is made of a mixture of paraffin and boron. The distance from the end capsule of the detectors to the neutron beam center was 4 cm; lead bricks of 10 cm thickness were used to surround the detectors as gamma shields for which the background count rate in the 0.2 ÷ 8 MeV range was guaranteed to be less than 400 counts per second. Two plates of 2 mm thick lead were placed [5] between the detectors and target to decrease the number of backscattered gamma-rays.

The electronic configuration that was used in those gamma-gamma coincidence experiments are shown in Fig.1. The detector signals are amplified with 572 amplifier (AMP) modules with a shaping time of 3 μ s and energy gain of about 1 keV per channel. The output signals of the amplifiers are digitized by 7072 analog-to-digital converter (ADC) modules. The timing signals of both detectors are put through 474 timing filter amplifier (TFA) modules. The shaped and amplified timing signals by 474 TFA are plugged into 584 CFD modules, which are used in slow rise time rejection option (SRT) mode. The CFD output signal of the first channel (using GPC20 detector) is used as 556 time-to-amplitude converter (TAC) start signal. The CFD output signal of the second channel (using GC2018 detector) is delayed 100 ns and served as a TAC stop signal. The full scale of TAC was set at 100 ns and output signal is digitized in 8713 ADC with selection of 1024 channels for a maximum 10 V input pulse. The TAC “Valid Convert” signal is used to gate 7072 ADC, and the delay for synchronizing with AMP output signal is implemented by interface software. The recorded coincident events have three values, including coincidence gamma-ray energies from detector 1, detector 2 and time interval between two γ -rays of pair events.

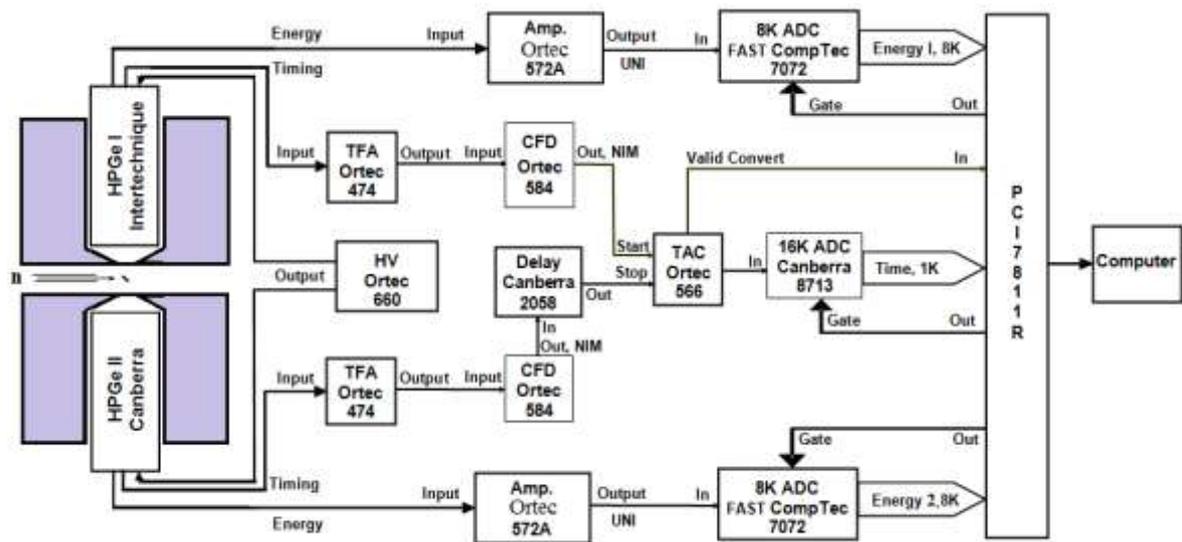


Fig.1. The electronics configuration.

The programming interface was set up in event-event coincidence mode. The data of the deposited gamma-ray energies and time intervals were recorded and processed off-line by summation of amplitude method.

In Fig.2, part of SACP spectra of ^{52}V and ^{64}Cu obtained from thermal neutron capture reactions in target nuclei of ^{51}V and ^{63}Cu respectively are presented. The sum energies of full - capture peaks of the cascades are marked here with value of final cascade energy. Fig.3

shows the intensity distribution of the cascade transitions to the ground states of ^{52}V and ^{64}Cu nuclei as a function of any cascade quantum energy [6].

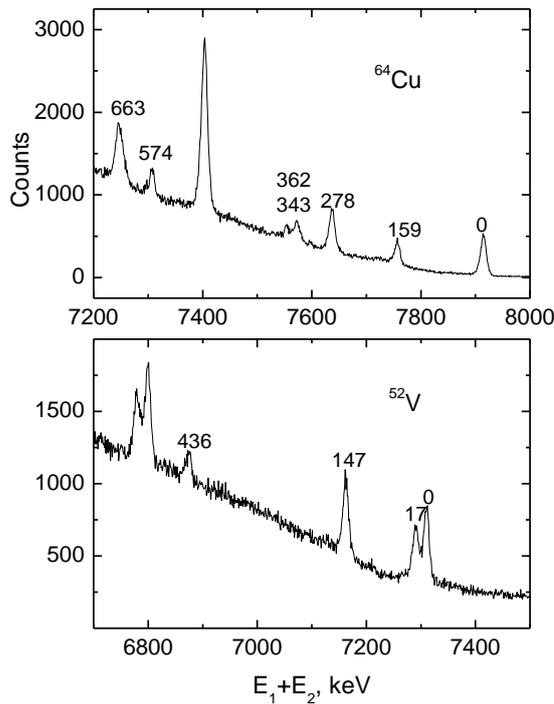


Fig.2. Sum of coincidence pulses spectra for ^{52}V and ^{64}Cu . Final cascade levels mark by E_f energies.

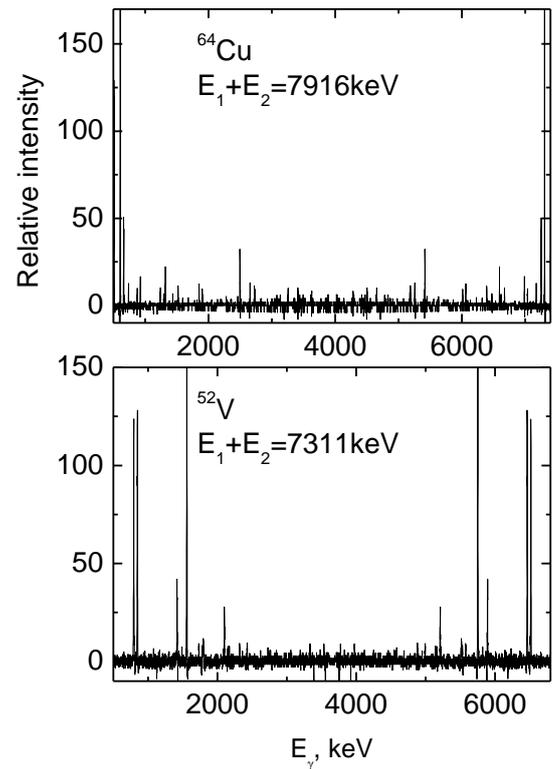


Fig.3. Two-step cascade on ^{52}V and ^{64}Cu ground states intensity distributions.

Spectroscopic data

Comparison of the theoretical model to the experimental results of cascade intensities after fitting ρ and Γ to their best approximation values needs a procedure of transforming the experimental distribution (the sum of the intensities of the different cascades with primary E_1 and secondary E_2 gamma-quanta are practically of the same value to the distribution of transition intensities for primary energy only. Procedure [7] for this purpose uses the fact that cascades with $E_1 > 0.5 B_n$ are mostly observed in the form of strong intensity and well resolved energy peaks, and the ones with $E_1 < 0.5 B_n$ form a continuous distribution of small amplitudes. Data for the energies of the primary transitions and the intensity of these cascades are listed in the tables 1 and 2. The order of quanta in the cascade is determined in this procedure and has lowest precision around $0.5 B_n$. But with this excitation energy, the error [7] in the determination of the order of the quanta has very the smallest influence on the approximated values ρ and Γ . This is a consequence of the procedure [7] and it does not change the absolute value of $I_{\gamma\gamma}$; and also, the sensitivity of the method in determining ρ and Γ to the form of the error distribution is small enough. The main factors limiting the reliability on the accuracy and precision of the found values of ρ and Γ are the increase of background resulting from incomplete energy absorption of the cascade quanta and the decrease on the

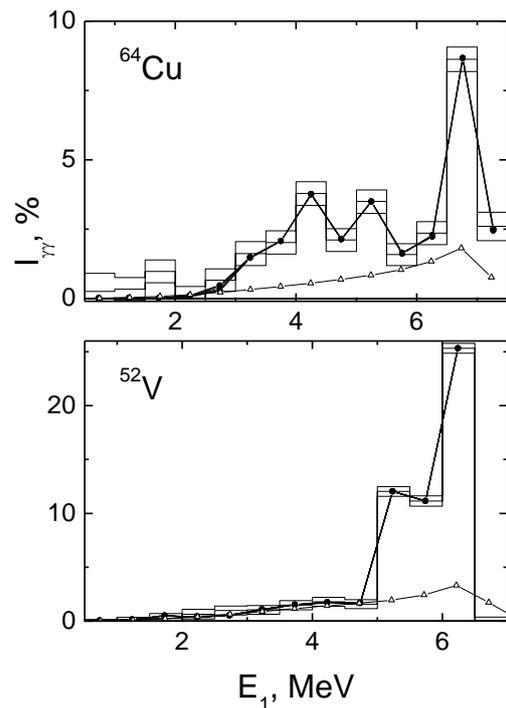
values of the absolute intensity of the cascades to the final levels with increasing of the final cascade level energy.

For this reason, the function $I_{\gamma\gamma} = F(E_1)$ is defined accordingly [7] for ^{52}V and ^{64}Cu only for final levels with $E_f \leq 0.147$ and $E_f \leq 0.278$ MeV. The experimental distributions of areas contain 54 and 43 per cent of compound-state decays respectively. Thermal neutron captures in ^{51}V and ^{63}Cu resonances are mainly defined by unbound resonances with unknown spins. Therefore, comparison of the experimental intensity with the best fitted curve was carried out with the assumption that the contribution of the s -resonances from spins $J = I-1/2$ and $I+1/2$ are almost the same.

The main parameters of cascade gamma decay

In Fig.4 are shown the distributions of $I_{\gamma\gamma} = F(E_1)$. Most part of experimental data errors are caused by errors of its normalization. Processing of experimental data for this purpose is performed through a comparison of relative intensity values to the most intense cascade transitions and their absolute values. The updated values for the intensities of the strongest primary transitions are obtained from the [8] files. The intensities of cascade branching ratios for secondary transitions in decay of intermediate level E_i are obtained from data which coincide with the given primary transitions according to the standard methodology used in coincidence data analysis.

Fig.4. Histograms are the sums of the experimental cascade intensities with their experimental errors in 0.5 MeV bins. Full points are the best fit for 6 different variants of approximation, triangles are the calculated spectra for models [9, 10] with $k(MI)=\text{const}$.



Comparisons of experimental cascade intensities with the expected distributions calculated on basis of the statistical theory with models [9, 10] for ^{52}V and ^{63}Cu nuclei are shown in Fig.4. In comparison, for different calculation models, it should be taken into account that the transfer coefficients of $I_{\gamma\gamma}$ (i.e., magnitude of deviations from different calculation models) for the necessary correction of level density functions, for example, can

reach a maximum value of ≈ 10 at $E_{\text{ex}} = 3.5$ MeV (Fig. 5). In the model [4] at this energy, the neutron and proton quasi-particles add two unpaired neutrons or protons for Cooper pair-breaking process.

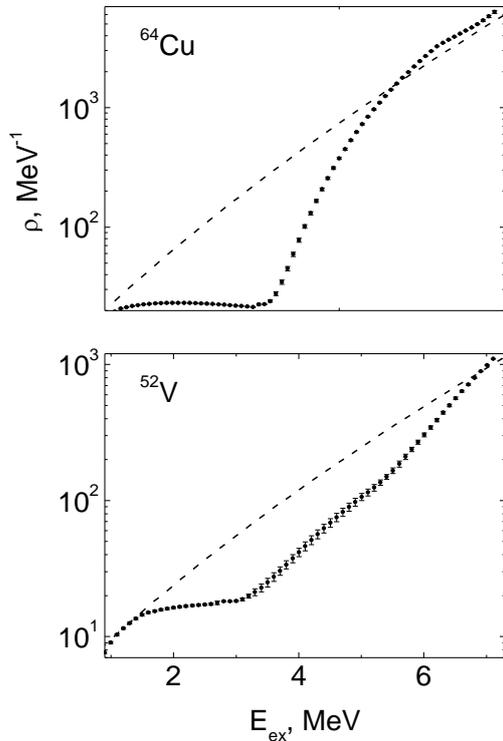


Fig.5. The most probable mean densities of intermediate levels of two-step cascades (full point with the bars) and their variations in several (minimal number is 6) different variants of approximations with the lowest χ^2 . Dash lines are the data of [10].

Pair breaking process inevitably modifies the structure of wave functions of all existing excited levels and changes the corresponding partial widths values (Fig. 6). Also the form of the level density as function of nucleus excitation energy is changed. For levels with wave functions of quasi-particle type, the value ρ [11] is uniquely defined by the level density g near the Fermi surface and excitation energy for which the number of quasi-particles is increased by 2 units.

A similar model that may describe the density of the vibrational levels for different number of phonons by the fitting method of experimental data is not yet available. Therefore, actually, a phenomenological representation for describing these density levels is used [4], but with the condition that the parameters E_u and E_v describing the rate of change of vibrational level density do not depend on the number of Cooper pair-breaking. Excellent reproduction of experimental data shows that very precise descriptions of the cascade gamma-decay of neutron resonance of arbitrary nuclei is notable without taking into account the super-fluid phases of nuclear matter. To further minimize systematic errors for the defined functions ρ and Γ , it is necessary first of all to develop a model for level density of vibrational type and a new type of radiative strength function for dipole gamma transitions for the neutron binding energy range and more.

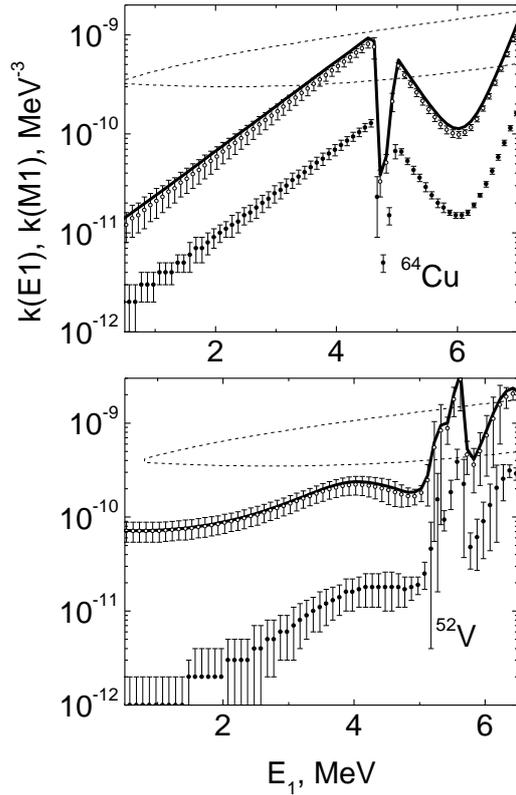


Fig.6. The strength functions of $E1$ -transitions (open points) and of $M1$ -transitions (close points) for odd-odd nuclei. Solid lines are their sums. Top dash line are the model calculation [12, 13], bottom lines are the model calculation [9] in sum with $k(M1)=\text{const}$.

Conclusion

Experimental information about the parameters of cascade gamma decay for compound-states of odd-odd light spherical nuclei has increased. Accurate approximation of functional dependencies $I_{\gamma\gamma} = F(E_1)$ is achieved under the new model for compound-state gamma-decay [4] without using any additional assumptions. From these results it can be concluded that:

- radical disagreement between the observed interval of changes in the number of Cooper pairs and the statistical assumptions about the density of excited levels [10] is found. The spacing between their thresholds is roughly of the order of two pairing energy;
- with the existing models [9, 10, 11], for energies of the primary cascade transitions below several MeV, strong deviations of the observed radiative strength functions $k = \Gamma / (A^{2/3} E_\gamma^3 D_\lambda)$ about their values are found.

Table1. Energies of primary E_1 and secondary E_2 transitions and their intermediate level E_i for nucleus ^{52}V . Values of the intensities, $i_{\gamma\gamma}$, are normalized to 10^5 decays.

E_1	E_2	E_i	$i_{\gamma\gamma}$
6517.7	793.5(2)	793.5	3479(197)
		645.7	10311(380)
6467.7	843.6(1)	824.4	4462(243)

E_1	E_2	E_i	i_{yy}
6465.3	845.9(2)	845.9	3794(204)
		698.1	746(102)
5891.0	1419.8(9)	1419.2	1091(84)
		1401.2	784(70)
		1272.6	153(48)
5857.2	1454.1(6)	1434.9	182(45)*
5752.0	1559.2(7)	1559.2	6524(274)
		1540.0	194(47)
5745.3	1566.0(7)	1546.8	184(39)*
5734.5	1576.8(5)	1557.6	260(48)
5604.2	1707.0(10)	1559.2	135(45)*
5581.0	1731.3(7)	1711.1	177(39)
		1732.4	141(39)
5552.2	1759.0(5)	1611.2	281(49)
5529.4	1781.9(6)	1781.9	203(35)*
5516.4	1795.9(5)	1794.8	344(45)
		1777.2	2655(126)
5386.4	1924.9(**)	1777.0	88(32)*
5210.8	2100.4(2)	2100.4	706(65)
5209.2	2102.0(2)	2082.8	483(57)
5191.3	2119.9(2)	1972.1	708(55)
5162.2	2149.0(17)	2149.0	124(35)
5160.5	2150.7(4)	2002.9	708(96)
5144.9	2167.8(17)	2147.2	3207(139)
		2169.1	211(39)
5018.3	2292.9(17)	2145.1	145(40)*
4993.2	2318.0(5)	2318.0	169(28)
		2170.2	103(37)
4882.6	2428.6(7)	2428.6	233(35)
		2409.4	341(38)
		2280.8	107(26)
4772.2	2539.1(5)	2519.9	184(32)
4566.8	2744.5(11)	2725.3	97(34)
4533.4	2777.8(8)	2758.6	134(32)
4485.5	2825.8(8)	2806.6	139(34)
4467.4	2843.9(8)	2824.7	130(34)*
4451.1	2860.1(2)	2840.9	477(52)
		2712.3	305(40)
4253.5	3057.8(10)	3057.8	83(26)
4118.9	3192.3(6)	3192.3	85(26)
		3044.5	155(31)
3976.2	3335.0(7)	3335.0	171(37)
3736.2	3575.1(8)	3555.9	150(34)
3716.7	3594.5(5)	3594.5	107(28)*
		3575.3	292(47)*

E_1	E_2	E_i	$i_{\gamma\gamma}$
3537.9	3773.3(7)	3773.3	107(30)*
		3754.1	192(39)*

Note. The marked by (*) cascades are absent in [8]. The sum of their intensities equals to 1.6% per decay.

Table2. Energies of primary E_1 and secondary E_2 transitions and their intermediate level E_i for nucleus ^{64}Cu . Values of the intensities, $i_{\gamma\gamma}$, are normalized to 10^5 decays.

E_1	E_2	E_i	$i_{\gamma\gamma}$
7307.3	608.7(1)	608.7	7383(303)
7300.1	615.9(16)	615.9	49(44)
7254.5	661.5(2)	663.0	894(104)
7251.5	664.5(2)	663.0	689(96)
7176.5	739.5(4)	739.5	231(46)
		580.2	1846(138)
7037.2	878.8(5)	878.8	200(32)
6989.0	927.0(2)	927.0	304(40)
		768.2	910(54)
		649.2	2784(208)
6674.5	1241.5(2)	1241.5	165(29)
		1082.2	303(30)
		963.2	245(27)
6617.9	1298.1(6)	1298.1	107(27)
		1138.8	642(42)
		1019.8	249(28)
6614.1	1301.9(8)	1301.9	47(21)*
6595.1	1320.9(3)	1320.9	494(50)
6478.1	1437.9(12)	1437.9	49(21)
		1159.6	27(13)
6414.6	1501.4(2)	1342.1	42(14)
		1521.3	291(38)
		1243.0	136(18)
6394.0	1522.0(5)	1362.7	390(32)
6364.5	1551.5(5)	1392.2	42(14)
		1273.2	100(17)
6307.5	1608.5(5)	1449.2	71(17)
6135.2	1780.8(2)	1502.5	109(17)
6115.4	1800.6(4)	1522.3	68(14)*
6063.3	1852.7(3)	1852.7	233(38)
		1574.4	102(17)
6037.5	1878.5(10)	1600.2	18(9)*
6017.2	1898.9(18)	1898.9	14(19)*
6010.7	1905.3(6)	1905.3	115(29)
		1627.0	34(13)
5771.9	2144.1(3)	2144.1	84(19)

E_1	E_2	E_i	i_{yy}
5727.6	2188.4(4)	2188.4	53(17)*
5709.0	2207.0(5)	2047.7	33(10)*
5617.5	2230.2(2)	2298.5	55(13)
		2142.7	178(18)
5554.6	2361.4(5)	2361.4	45(13)
		2083.1	179(18)
5480.9	2435.1(9)	2156.8	27(11)*
5452.2	2463.8(3)	2463.8	64(21)
5417.4	2498.6(15)	2498.6	589(61)
		2339.3	285(30)
5416.2	2499.8(6)	2499.8	221(40)
5407.2	2508.8(6)	2349.5	45(16)
5258.6	2657.4(13)	2657.4	221(36)
		2379.1	19(6)
5189.3	2727.2(3)	2726.7	175(32)
		2449.3	37(10)
5183.2	2733.3(3)	2732.8	97(23)
		2574.5	244(30)
5150.3	2765.7(5)	2606.4	137(23)
5138.9	2777.1(85)	2498.8	67(11)
5057.8	2858.2(3)	2698.9	68(16)*
5021.6	2894.4(4)	2894.4	35(34)
4981.2	2934.8(5)	2775.5	49(14)
4977.2	2938.8(6)	2660.5	53(18)*
4781.4	3134.6(4)	3134.6	165(36)*
4733.1	3182.9(4)	3023.6	82(19)*
4657.7	3258.3(4)	3258.3	219(29)
		2980.0	124(23)
4602.6	3313.4(3)	3154.1	501(44)
4502.8	3412.2(4)	3412.2	53(27)
		3255.0	64(16)
4497.1	3418.9(4)	3140.6	255(33)*
4491.7	3424.3(2)	3265.0	50(15)*
4477.3	3438.7(2)	3279.4	76(18)*
4324.1	3591.9(**)	3313.6	12(195)*
4320.6	3595.4(8)	3436.1	202(28)
		3317.1	399(405)
4315.5	3600.5(6)	3441.2	136(23)
4285.8	3630.2(10)	3630.2	144(29)
		3470.9	184(27)
4259.4	3656.6(4)	3378.3	73(18)*
4233.5	3682.5(7)	3523.2	32(14)*
4205.5	3710.6(4)	3432.2	97(24)
4137.8	3778.2(1)	3618.9	69(15)*
4102.8	3813.2(2)	3653.9	33(10)*

E_1	E_2	E_i	$i_{\gamma\gamma}$
3914.8	4001.2(8)	3722.9	110(24)*
3884.4	4031.6(7)	4031.6	78(23)
3844.0	4072.0(8)	3912.7	111(24)
3776.9	4139.1(8)	3979.8	80(22)
3590.0	4326.0(6)	4166.7	90(19)

Note. The marked by (*) cascades are absent in [8]. The sum of their intensities equals to 1.4% per decay. In the region of ρ step-like structure approximation, level density of the ^{52}V predicts 35 intermediate levels below $E_i = 4$ MeV. Table 1 contains 25. For ^{64}Cu below 4 MeV 65 intermediate levels are found instead of 53 from the reference tables.

REFERENCES

- [1] *Vasilieva E.V., Sukhovej A.M., Khitrov V.A.*, Phys. At. Nucl., **64(2)**(2001)153. P.153;(nucl-ex/0110017).
- [2] *Sukhovej A.M., Khitrov V.A.*, Phys. Part. Nucl., **36**(2005)359.
- [3] *Kravtsov V.A.*, *Atomic Masses and Binding energy of Nuclei* (Atomizdat, Voscov, 1965)
- [4] *Sukhovej A.M., Khitrov V.A.* Proc. of the XXI International Seminar on Interaction of Neutrons with Nuclei, Alushta, Ukraine, May 2013, E3-2014-13, Dubna, 2014, p.172.
- [5] *Boneva S.T. et all*, Sov. J. Part. Nucl., **22(2)** (1991)232.
- [6] *Sukhovej A.M., Khitrov V.A.*, Instrum. Exp. Tech., **27** (1984)1071.
- [7] *Boneva S.T., Sukhovej A.M., Khitrov V.A.*, Nucl. Phys. A., **589**(1995)293.
- [8] <http://www.bnl.gov/ENSDF>
- [9] *Kadmenskij S.G., Markushev V.P., Furman W.I.*, Sov. J. Nucl. Phys., **37**(1983)165.
- [10] *Dilg W., Schantl W., Vonach H., Uhl M.*, Nucl. Phys., **217**(1973)269.
- [11] *Strutinsky V.M.*, Proc. of the Inter. Congress on Nuclear Physics, Paris, 1958, p.617.
- [12] *Axel P.*, Phys. Rev., **126**(1962)71.
- [13] *Brink D.M.*, Ph. D. Thesis. Oxford University, 1955.