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TWO-STEP CASCADES OF THE ^{187}W COMPOUND NUCLEUS γ-DECAY

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Two-step cascades from the ^{186}W(n,2γ)^{187}W reaction have been studied in the $\gamma-\gamma$ coincidence experiment carried out in Řež. Their total intensity is evaluated with respect to the final level of cascades at $\approx$ 1.9 MeV. The processes of the cascade γ-decay of this nucleus, like of all nuclei previously studied in analogous experiments, can not be described without taking into account the influence of nuclear structure at energies lower than at least a half of the neutron-binding energy. The decay scheme of ^{187}W, including 386 cascades, is determined up to the excitation energy $\sim$ 3 MeV. It contains data about 196 excited levels of this nucleus with the most probable spins 1/2 and 3/2. As in the earlier studied nuclei, the population of the intermediate levels by the most intense cascades may indicate a harmonic character of the states involved.

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1. Introduction

At present, the only technique for detailed and reliable study of properties of any nucleus in the region of neutron-binding energy is the measurement of two-step cascades from the thermal neutron capture, which connects the compound state at the excitation energy B_n with the low-lying levels at E_f. The number of such cascades, their total intensity in the given energy region of intermediate levels are determined by the total number of levels available for excitation in the studied process and by the energy derivative of the partial width of γ transition of the given energy and multipolarity. Here, both level density and partial widths of cascade transitions are determined by the nuclear structure.

Its specific character may be revealed in the B_n region only if one has reliable experimental data on the main parameters of the cascade γ decay of the compound state. Their determination as the first stage of the complex experiment, in its turn, is related to obtaining of the maximum amount of spectroscopic information on the most intense cascades.

The two-step cascades to low-lying levels of the studied nucleus may give quite rich and, above all, reliable information on the excited states and modes of their γ-decay, even without the use of additional spectroscopic information. The intensity of all possible two-step cascades averaged over certain energy region of their intermediate levels allows one to obtain the information on the nuclear properties at the excitation energies higher than ≈ 2 MeV. It cannot be obtained by other methods because of insufficient energy resolution of spectrometers.

The total amount of information obtained in an experiment is mostly determined by the efficiency and resolution of Ge-detectors used to record coincidences.

The cascade γ-ray transitions following thermal neutron capture in ^{187}W have been studied for the first time [1] in the experiment carried out in Riga using $\sim 10\%$ Ge(Li) detectors. Considerably larger amount of information about them has been extracted from the present experiment performed in Řež. It is obtained regardless of the fact that the data have been accumulated at the neutron capture in the sample enriched in ^{184}W isotope with the ^{186}W as an admixture. Spectroscopic data for ^{185}W have been published in Ref. [2], and the most reliable data on the level density and radiative strength functions in four tungsten isotopes are presented in Ref. [3].

2. Experiment

Two-step γ cascades from the thermal neutron capture were studied with the $\gamma-\gamma$ coincidence spectrometer at the thermal neutron beam of the LWR-15 reactor at INP. In the experiment, the spectrometer [4] with two HPGe-detectors with the relative efficiencies of 25% and 28% was used. The ^{184}W sample with the mass of 1190 mg contained 17 mg of ^{182}W, 32 mg of ^{183}W and 38 mg of ^{186}W as admixtures. Available cross sections of thermal neutron capture [5] in tungsten provided 8.8%, 8%, 47% and 36% of captures in ^{182}W, ^{183}W, ^{184}W and ^{186}W, respectively.

In contrast to other known methods to study the process of thermal neutron capture, the method of summation of amplitudes of coincident pulses makes it possible [6] to obtain quite reliable data not only for a purely monoisotopic target but also for a mixture of several isotopes at the comparable number of captures in each of them with attraction of minimal amount of additional and well-known information (neutron binding energies and the parameters of lowest-lying excited levels). No doubt, in this case the quality of experimental information will inevitably become worse due to:

a) an increase of the Compton background under the full capture peaks of lower energies;

b) a possible peak overlap in cases when the total energy $E_1 + E_2 = B_n - E_f$ of cascades in different isotopes coincides within the limits of experimental resolution (including single- and double-escape peaks).

However, rather high efficiency of detectors and their excellent resolution (FWHM=5 keV for peaks with $E_1 + E_2 = 5-6$ MeV in the sum amplitudes spectrum) allow one to obtain data of acceptable quality even in this case.

The main part of the obtained spectrum of sum amplitudes of coinciding pulses is given in Fig. 1. Here the statistics of useful coincidences for cascades with the largest energy is much higher than in the experiment carried out in Riga [1]. As a result, it turned out to be possible to obtain qualitative distributions of the cascade intensity with $E_c = E_1 + E_2 = B_n - E_f$ as a function of energy of one of transitions for 5, 6, 16 and 5 distributions for compound nuclei ^{183,184,185,187}W, respectively. An example, of one of them is shown in Fig. 2.

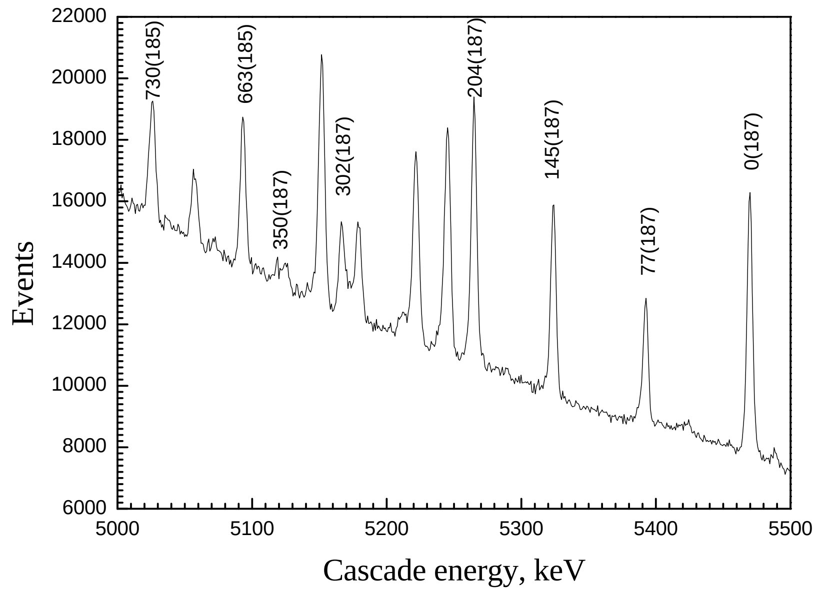

Fig. 1. Part of the sum amplitude of the spectrum of coinciding pulses for the target enriched in ^{184}W. *Peaks are marked by energies* (keV) *of the final cascade levels and (in parentheses) by mass of the corresponding isotope. Registration threshold of any cascade* γ *quantum was 520* keV.

Each cascade in a spectrum is presented by a pair of peaks of equal area and width [7] regardless of the energy of cascade transitions. Almost all distributions of the type given in Fig. 2 have the resolution from 1.5 to 2.4 keV at their edges and in the center, respectively. The probability of observing cascades of the smallest intensity in the form of a pair of peaks in such a spectrum is determined only by the

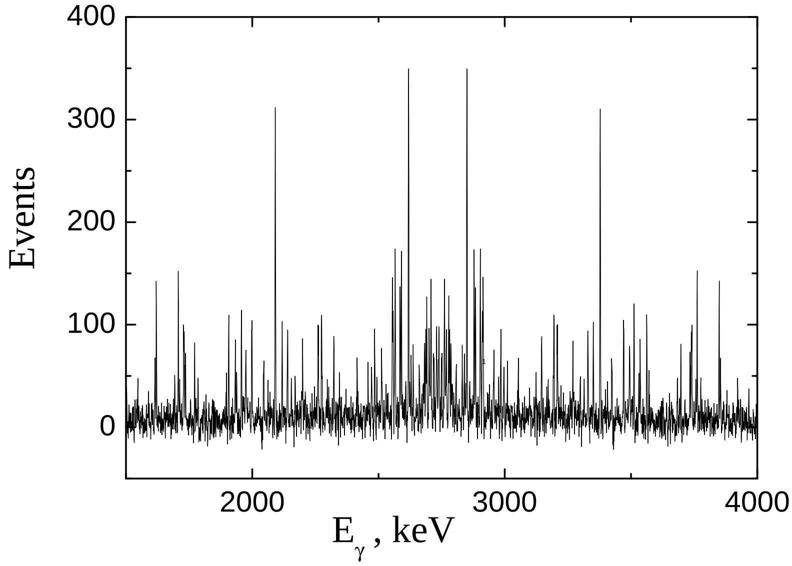

Fig. 2. Central part of the distribution of cascade intensities for the ground state of ^{187}W.

amplitude of the "noise" line. Its value increases for an increase of the background under peaks of the sum spectrum. Therefore, their registration threshold L_c for the analyzed spectrum $E_c =$ const is practically determined only by the total number of background events under the spectrum peaks shown in Fig. 1. It increases from 1 to 3 events per 10^4 decays at energies E_c from 5.8 to 4.7 MeV, respectively.

For the number of high-lying final levels of cascades (high E_f) from the spectrum partially presented in Fig. 1, one may determine the area of the corresponding peaks. However, bad signal/background ratio does not allow one to obtain qualitative intensity distribution (similar to the one presented in Fig. 2) for such cascades. Nevertheless, the realistic estimation of their sum intensity may give the additional information on the properties of excited states of the studied isotopes of W.

3. Spectroscopic information

The method of constructing the decay scheme using the statement on the constancy of energy of the primary transition $E_1 = B_n - E_i$ in cascades with different sum energy $E_c = E_1 + E_2$ is described in Ref. [8]. Within the framework of the method of maximum likelihood it uses the Gaussian multidimensional distribution for the most accurate identification of similar γ-transitions in different sum spectra with the statistical error on the order of $0.5-1$ keV of determination of their energy. The method provides [9] a high accuracy of decay scheme construction which includes several hundreds of cascade transitions even with errors of the order of $\simeq 1.5$ keV or more. The obtained decay scheme of ^{187}W is shown in Table 1.

TABLE 1. Decay scheme of ^{187}W state produced by slow-neutron absorption in ^{186}W, E_1 and E_2 are energies of cascade quanta, E_i are energies of intermediate levels, $i_{\gamma\gamma}$ are absolute intensities (per 10^5 decays). All energies are in keV.

E_1	E_i	E_2	$i_{\gamma\gamma}$
5321.5	145.7(1)	145.7	21(4)
5262.5	204.7(0)	204.7	90(6)
4685.1	782.1(1)	782.1	753(16)
		636.4	42(6)
		577.3	1225(35)
4663.5	803.7(3)	658.0	41(6)
		598.9	17(8)
4655.4	811.8(2)	734.4	20(4)
4651.1	816.1(1)	816.1	166(16)
		738.7	86(6)
		670.4	172(10)
		611.3	114(11)
4627.0	840.2(1)	840.2	885(33)
		762.8	282(11)
		694.5	416(15)
		635.4	188(14)
4575.3	891.9(4)	891.9	453(25)
		814.5	112(7)
		746.2	268(12)
		687.1	15(6)
		588.6	199(20)
4566.2	901.0(5)	823.6	51(10)
		597.7	75(14)
4558.2	909.0(2)	909.0	102(18)
		831.6	88(10)
4556.4	910.8(3)	910.8	47(11)
4487.8	979.4(1)	979.4	40(7)
		833.7	64(10)
		774.6	18(5)
4478.0	989.2(7)	989.2	47(7)
		787.0	23(5)
		784.4	26(5)
4448.8	1018.4(1)	1018.4	159(11)
		941.0	66(5)
		872.7	212(16)
		813.6	107(11)
		715.1	57(6)
4385.0	1082.2(1)	1082.2	353(17)
		936.5	43(8)
		877.4	230(15)
4381.6	1085.6(1)	782.3	99(13)
4372.7	1094.5(2)	1094.5	28(6)
		889.7	57(8)
		791.2	44(11)
4332.0	1135.2(1)	1135.2	104(9)
		1057.8	177(6)
		989.5	82(8)
		930.4	37(8)
		831.9	57(18)
4250.2	1217.0(1)	1139.6	146(12)
		1071.3	701(23)
		1012.2	414(15)
4158.8	1308.4(3)	1231.0	36(7)
		1005.1	42(12)
4154.6	1312.6(2)	1107.8	41(6)
4145.3	1321.9(3)	1018.6	32(9)
4138.6	1328.6(1)	1025.3	144(14)
4119.9	1347.3(2)	1347.3	60(4)
		1201.6	19(8)
4104.0	1363.2(6)	1285.8	12(7)
4082.5	1384.7(10)	1384.7	32(4)
		1307.3	18(4)
		1239.0	52(8)
		1179.9	82(5)
4025.5	1441.7(3)	1138.4	38(10)
4022.9	1444.3(3)	1366.9	14(4)
4016.7	1450.5(2)	1450.5	152(7)
		1373.1	26(4)
		1304.8	19(4)
3965.6	1501.6(1)	1501.6	18(3)
		1355.9	40(4)
		1296.8	83(6)
3932.2	1535.0(3)	1535.0	12(4)
3921.5	1545.7(1)	1545.7	19(3)
		1400.0	196(10)
		1340.9	53(5)
3902.1	1565.1(3)	1419.4	25(8)
		1360.3	150(7)
3871.6	1595.6(3)	1449.9	17(4)
3853.9	1613.3(7)	1613.3	25(5)
		1535.9	13(4)
		1408.5	17(5)
3848.1	1619.1(1)	1619.1	63(5)
		1541.7	31(4)
		1473.4	18(5)
		1414.3	436(11)
3823.7	1643.5(2)	1497.8	23(5)
3818.0	1649.2(3)	1345.9	35(9)
3804.2	1663.0(3)	1585.6	38(4)
		1517.3	44(4)
		1458.2	31(5)
3794.0	1673.2(1)	1595.8	32(4)
3775.7	1691.5(3)	1691.5	23(3)
		1614.1	16(4)
		1486.7	22(4)
		1388.2	29(8)
3761.3	1705.9(3)	1705.9	66(4)
		1628.5	9(4)
		1501.1	20(4)
3755.5	1711.7(2)	1711.7	18(3)
3747.8	1719.4(2)	1416.1	45(9)
3740.5	1726.7(3)	1726.7	39(4)
		1649.3	15(3)
		1581.0	103(7)
		1521.9	78(5)
		1423.4	81(10)

Table 1. (cont.)

E_1	E_i	E_2	$i_{\gamma\gamma}$
3738.1	1729.1(2)	1729.1	46(4)
		1583.4	68(6)
		1524.3	67(5)
		1425.8	69(9)
3732.6	1734.6(1)	1734.6	35(3)
3712.4	1754.8(3)	1754.8	14(3)
3696.4	1770.8(2)	1770.8	38(4)
		1566.0	29(4)
3640.0	1827.2(4)	1827.2	10(4)
3620.1	1847.1(6)	1642.3	24(4)
		1543.8	20(6)
3578.7	1888.5(3)	1585.2	21(6)
3576.0	1891.2(2)	1813.8	8(3)
		1686.4	43(4)
		1587.9	29(6)
3570.0	1897.2(3)	1897.2	17(4)
3561.8	1905.4(2)	1905.4	56(5)
		1828.0	34(4)
		1759.7	237(8)
		1700.6	154(6)
		1602.1	57(6)
3536.2	1931.0(1)	1726.2	42(5)
		1627.7	41(14)
3533.7	1933.5(7)	1933.5	39(4)
		1787.8	91(6)
		1728.7	21(5)
		1630.2	87(15)
3530.3	1936.9(2)	1936.9	22(4)
		1859.5	38(4)
		1791.2	13(4)
		1732.1	20(4)
		1633.6	80(7)
3523.3	1943.9(3)	1640.6	29(6)
3516.8	1950.4(1)	1647.1	63(7)
3511.2	1956.0(2)	1956.0	60(5)
		1878.6	35(4)
		1751.2	24(5)
		1652.7	93(8)
3505.1	1962.1(3)	1884.7	14(4)
		1816.4	17(5)
3501.3	1965.9(5)	1965.9	10(4)
3493.5	1973.7(2)	1973.7	39(4)
		1896.3	70(5)
		1828.0	50(5)
		1768.9	22(5)
		1670.4	39(6)
3486.1	1981.1(1)	1677.8	74(7)
3470.1	1997.1(2)	1997.1	56(5)
		1919.7	88(5)
		1851.4	16(5)
		1792.3	199(8)
		1693.8	54(7)
3453.0	2014.2(3)	1868.5	22(5)
3437.5	2029.7(3)	1726.4	24(6)
3423.0	2044.2(1)	2044.2	34(4)
		1966.8	39(5)

E_1	E_i	E_2	$i_{\gamma\gamma}$
		1740.9	47(6)
3408.5	2058.7(2)	1981.3	21(5)
		1853.9	12(5)
3405.0	2062.2(5)	1984.8	11(4)
3398.0	2069.2(10)	2069.2	10(4)
		1923.5	16(5)
		1765.9	20(6)
3396.1	2071.1(3)	1925.4	24(5)
3383.9	2083.3(2)	1937.6	25(5)
3377.0	2090.2(4)	2090.2	166(8)
		2012.8	11(4)
		1944.5	35(6)
		1885.4	57(5)
		1786.9	32(7)
3349.8	2117.4(8)	2117.4	49(4)
		1814.1	51(8)
3343.4	2123.8(2)	1978.1	29(6)
		1919.0	24(5)
3337.3	2129.9(2)	1925.1	29(5)
3328.7	2138.5(4)	2138.5	64(6)
		2061.1	21(4)
		1933.7	16(5)
3325.0	2142.2(4)	1937.4	14(5)
3317.2	2150.0(2)	2004.3	38(6)
		1945.2	40(5)
		1846.7	29(8)
3313.6	2153.6(2)	2153.6	21(4)
		2076.2	25(4)
3298.6	2168.6(6)	2168.6	25(4)
		2091.2	15(5)
		2022.9	31(6)
3286.7	2180.5(3)	1975.7	19(5)
3272.3	2194.9(3)	2194.9	16(3)
3268.6	2198.6(1)	2198.6	36(4)
3262.9	2204.3(4)	2204.3	11(4)
3258.0	2209.2(3)	2209.2	16(4)
3239.0	2228.2(2)	2150.8	41(5)
		2082.5	35(6)
3234.6	2232.6(2)	2027.8	35(5)
3232.8	2234.4(5)	2088.7	15(6)
3225.8	2241.4(1)	2095.7	260(12)
		2036.6	165(8)
		1938.1	116(10)
3209.0	2258.2(2)	2258.2	24(6)
		2180.8	20(4)
3206.6	2260.6(2)	2260.6	40(6)
3200.4	2266.8(3)	1963.5	33(8)
3198.2	2269.0(3)	2064.2	13(4)
3194.0	2273.2(7)	2273.2	59(6)
		2127.5	19(6)
3191.5	2275.7(3)	2275.7	21(5)
		2198.3	17(4)
		2070.9	62(5)
3184.2	2283.0(4)	2137.3	16(5)
3179.3	2287.9(2)	2083.1	35(5)
3170.7	2296.5(3)	2296.5	18(4)

Table 1. (cont.)

E_1	E_i	E_2	$i_{\gamma\gamma}$	E_1	E_i	E_2	$i_{\gamma\gamma}$
3167.3	2299.9(3)	2095.1	15(5)	2970.0	2497.2(12)	2419.8	12(4)
3165.1	2302.1(3)	2302.1	16(4)			2292.4	49(6)
3161.9	2305.3(2)	2159.6	34(5)	2964.1	2503.1(5)	2503.1	9(4)
		2100.5	17(5)	2958.0	2509.2(2)	2363.5	30(5)
3160.3	2306.9(3)	2229.5	14(4)	2956.0	2511.2(2)	2511.2	33(5)
3152.0	2315.2(3)	2315.2	10(4)	2953.2	2514.0(9)	2514.0	16(4)
		2110.4	14(5)			2368.3	23(5)
3145.0	2322.2(1)	2322.2	47(4)			2210.7	27(7)
3123.5	2343.7(6)	2343.7	18(4)	2939.6	2527.6(7)	2527.6	15(4)
		2266.3	14(4)			2450.2	41(4)
		2198.0	36(5)			2381.9	18(5)
		2138.9	48(5)			2322.8	101(7)
3120.6	2346.6(6)	2346.6	9(4)	2935.6	2531.6(11)	2454.2	27(4)
3115.3	2351.9(4)	2351.9	12(4)			2385.9	29(6)
3110.7	2356.5(1)	2210.8	44(5)			2326.8	14(5)
3099.8	2367.4(2)	2221.7	29(5)	2932.7	2534.5(1)	2388.8	64(6)
		2162.6	21(5)	2921.6	2545.6(1)	2242.3	64(7)
3097.1	2370.1(2)	2370.1	14(5)	2914.0	2553.2(4)	2553.2	66(5)
		2292.7	32(5)			2475.8	11(4)
		2224.4	35(5)			2249.9	25(7)
3092.2	2375.0(3)	2229.3	20(5)	2911.0	2556.2(8)	2410.5	23(5)
3086.3	2380.9(3)	2176.1	19(5)			2252.9	67(8)
3083.4	2383.8(3)	2238.1	17(5)	2909.6	2557.6(4)	2480.2	11(4)
3073.1	2394.1(3)	2248.4	20(5)	2904.8	2562.4(2)	2562.4	24(4)
3067.8	2399.4(2)	2322.0	20(4)	2902.5	2564.7(4)	2564.7	87(6)
3055.8	2411.4(6)	2334.0	43(4)			2487.3	14(4)
		2265.7	22(5)			2359.9	35(5)
		2108.1	29(8)	2895.6	2571.6(5)	2425.9	17(5)
3052.4	2414.8(5)	2414.8	31(9)			2268.3	29(7)
		2337.4	13(4)	2893.3	2573.9(3)	2369.1	20(5)
		2269.1	34(5)	2884.4	2582.8(3)	2378.0	23(5)
		2210.0	19(5)	2876.7	2590.5(4)	2590.5	91(7)
3040.4	2426.8(2)	2222.0	29(5)			2513.1	14(4)
		2123.5	22(7)	2866.6	2600.6(4)	2395.8	23(5)
3037.9	2429.3(4)	2283.6	20(6)			2297.3	29(9)
3033.5	2433.7(2)	2228.9	24(5)	2860.3	2606.9(3)	2606.9	21(5)
3031.2	2436.0(3)	2290.3	28(6)	2854.1	2613.1(3)	2408.3	18(5)
3028.9	2438.3(2)	2360.9	12(4)	2849.6	2617.6(2)	2617.6	202(9)
		2292.6	25(6)			2471.9	146(8)
3020.2	2447.0(2)	2242.2	25(5)	2843.2	2624.0(7)	2624.0	16(4)
3009.6	2457.6(2)	2457.6	24(4)			2419.2	65(5)
3005.6	2461.6(5)	2315.9	17(5)	2839.3	2627.9(2)	2627.9	30(5)
		2256.8	28(5)			2482.2	34(5)
2996.3	2470.9(3)	2470.9	27(5)			2423.1	37(5)
		2393.5	33(4)			2324.6	39(8)
		2325.2	25(5)	2831.0	2636.2(7)	2636.2	31(5)
		2266.1	29(5)			2332.9	35(8)
2989.7	2477.5(4)	2174.2	25(7)	2829.7	2637.5(4)	2432.7	31(13)
2982.7	2484.5(4)	2484.5	43(4)	2826.3	2640.9(4)	2563.5	12(4)
		2181.2	31(7)	2821.0	2646.2(2)	2568.8	22(4)
2980.6	2486.6(2)	2281.8	29(5)			2441.4	19(5)
2978.0	2489.2(4)	2343.5	16(5)	2816.8	2650.4(3)	2347.1	40(9)
2975.2	2492.0(5)	2492.0	22(4)	2813.0	2654.2(8)	2576.8	12(4)
		2414.6	21(4)			2350.9	89(10)
		2346.3	48(5)	2806.5	2660.7(2)	2660.7	28(4)
		2287.2	43(6)	2788.4	2678.8(3)	2601.4	20(4)

Table 1. (cont.)

E_1	E_i	E_2	$i_{\gamma\gamma}$	E_1	E_i	E_2	$i_{\gamma\gamma}$
		2474.0	12(4)			2703.6	11(4)
		2375.5	27(8)			2635.3	20(5)
2785.9	2681.3(1)	2681.3	40(5)			2576.2	24(5)
2780.9	2686.3(4)	2481.5	14(5)	2670.5	2796.7(2)	2651.0	18(5)
2777.1	2690.1(1)	2690.1	57(6)			2591.9	16(5)
2767.6	2699.6(1)	2699.6	44(5)	2660.9	2806.3(1)	2601.5	63(5)
2760.1	2707.1(1)	2707.1	75(6)	2633.9	2833.3(4)	2530.0	24(8)
2752.8	2714.4(8)	2637.0	14(4)	2632.4	2834.8(8)	2757.4	14(5)
		2509.6	24(5)			2689.1	44(6)
2749.5	2717.7(2)	2717.7	32(5)	2629.6	2837.6(5)	2760.2	22(4)
		2572.0	19(7)			2691.9	21(6)
2744.6	2722.6(7)	2645.2	35(4)			2534.3	24(8)
		2576.9	20(5)	2595.9	2871.3(3)	2871.3	9(4)
		2419.3	33(9)			2666.5	18(5)
2741.6	2725.6(1)	2520.8	94(6)	2585.0	2882.2(7)	2882.2	76(6)
2739.0	2728.2(4)	2728.2	40(6)			2804.8	13(4)
		2650.8	12(4)			2736.5	73(7)
		2424.9	27(8)			2677.4	26(5)
2735.0	2732.2(9)	2732.2	22(6)	2570.8	2896.4(2)	2750.7	52(7)
		2586.5	17(6)			2691.6	13(5)
2733.6	2733.6(2)	2528.8	27(5)	2557.5	2909.7(1)	2909.7	58(5)
2730.3	2736.9(3)	2591.2	20(5)			2832.3	49(5)
2719.9	2747.3(3)	2601.6	20(5)			2704.9	20(5)
2708.1	2759.1(7)	2613.4	28(5)			2606.4	36(8)
		2554.3	31(5)	2537.0	2930.2(2)	2930.2	14(4)
2703.9	2763.3(4)	2617.6	14(5)			2784.5	20(5)
2689.0	2778.2(4)	2573.4	14(5)	2431.5	3035.7(2)	2958.3	29(4)
2686.2	2781.0(6)	2781.0	47(5)			2830.9	33(13)

1.Cascades with the one secondary γ-transition can have the reverse order of quanta.

2. Only statistical errors for energies and intensit1es are given.

Analysis of the experimental data requires the relation of the peak areas of resolved cascades to their absolute intensities (percent per decays of compound state). However, the direct solution of this problem by way of usual techniques of the normalization of experiment for calibrating peak areas in this case is practically impossible due to the uncontrollability of the conditions: first of all, due to the impossibility to determine the number of captures in the target and the absolute efficiency of the spectrometer in the used experimental "closed" geometry [4] with the error less than $\sim 10\%$. However, this problem is easily solved by the normalization of cascade intensities using their absolute value $A_{\gamma\gamma}$ calculated for the strongest one of them using the expression $A_{\gamma\gamma} = i_1 * B_r$, where absolute intensities of primary transitions i_1 are taken from literature, and branching coefficients B_r are determined usually from the same array of γ–γ coincidences accumulated in the experiment. The use of the maximum set of cascades in such normalization makes it possible to minimize both statistical and systematic errors of our experiment and reduce them practically to the errors of i_1. In addition, the experiment on independent determination of absolute intensities i_1 of γ rays from thermal neutron capture has been carried out for the tungsten isotopes mentioned above. For this purpose, the spectra for enriched isotopes ^{184,186}W and ^{nat}W have also been measured. The experiment with isotope ^{186}W has allowed one to redefine absolute intensities of primary transitions of the radiative thermal neutron capture in this nucleus with the maximum possible accuracy by comparing their relative intensity with the known intensities of γ-quanta from the ^{187}W β-decay. For relative values of the earlier published data [10] on i_1, the normalizing coefficient equals 0.0349. The values of intensities of primary transitions for cascades, according to which the normalization of sums of cascade intensities has been performed with the same intermediate level, have been obtained in this way and are presented in Table 2. Because of the lack of systematic errors of determining the cascade intensities, the relation $R = \sum i_{\gamma\gamma}/i_1$ must be decreased for lower E_1. The values of R exceeding 1 are used for certain estimation of total errors of experimental data both in the present experiment and in the measurement of single's γ-spectra after thermal neutron capture. It should be pointed out that due to the considerably differing background conditions in cascade coincidence and single γ-spectra measurement, the contribution of the systematic errors to the i_1 may be greater than of the $i_{\gamma\gamma}$ errors, at least, for the smallest values of E_1.

TABLE 2. Energies E_1 and absolute intensities (% of decays) of the primary γ transitions i_1 used to normalize the cascade intensities. $\sum i_{\gamma\gamma}$ are the observed sum of the cascade intensities with the corresponding primary transitions.

E_1,	i_i	$\sum i_{\gamma\gamma}$
4685.1(1)	1.75(2)	1.88(3)
4627.0(1)	1.47(2)	1.62(4)
4575.3(4)	0.92(1)	0.95(3)
4448.8(1)	0.55(2)	0.54(2)
4385.0(1)	0.65(1)	0.59(2)
4332.0(3)	0.41(1)	0.42(2)
4250.2(1)	1.19(5)	1.09(3)
3536.2(4)	0.41(1)	0.37(2)
3511.2(2)	0.42(1)	0.20(2)
Sum	7.77(7)	7.66(9)

The total summarized cascade intensity $I_{\gamma\gamma} = \sum i_{\gamma\gamma}$ with $E_1 + E_2$=const (including the continuum of weak unresolved cascades) with the registration threshold of any cascade quantum $E_\gamma > 520$ keV is given in Table 3. The number of extracted cascades is restricted by the experimental conditions. The peak/background ratio

TABLE 3. Sum energy of the cascade E_c, calculated intensity $I_{\gamma\gamma}^{cal}$ and the experimental one $I_{\gamma\gamma}^{exp}$ (% of decays) of the two-step cascades in ^{187}W.

E_c,	E_f,	$J^\pi, K[Nn_z\Lambda]$	$I_{\gamma\gamma}^{exp}$	$I_{\gamma\gamma}^{cal}$ [13,14]
5467	0.	3/2- 3/2[512]	8.6(6)	9.2
5389	77	5/2- 3/2[512]	3.6(3)	4.0
5321	145	1/2- 1/2[510]	6.6(9)	6.2
5261	204	3/2- 1/2[510]	7.6(7)	5.9
5164	302	5/2- 1/2[510]	4.4(3)	2.5
Sum			30.8(14)	27.8

in the spectrum of sum amplitude decreases for higher energies of the final level of cascades E_f. This has not allowed obtaining of reliable information about the function $i_{\gamma\gamma} = F(E_\gamma)$ in ^{187}W for $E_f > 0.5$ MeV.

4. *Background*

Each spectrum in our analysis is represented by the distribution of cascade intensities with the given sum energy consisting of three components:

(i) true cascades in the form of pairs of resolved peaks and

(ii) their overlaping continuous distribution of small amplitude;

(iii) the "noise" line - a part (from larger summarized energy) absorbed by detectors and subsequently subtracted.

Total area of the "noise" line in any spectrum equals zero to high accuracy but its local structures may give quite significant distortions of the form of obtained spectra. At the same time, main distortions are caused by the effect of full energy capture by one of the cascade quanta and partly by another quantum. They manifest themselves as local sign-changing structures of the "noise" line, symmetrical relative to the spectrum center. As shown in Ref. [9], they influence significantly the spectrum shape only in the cases when the cascade of greater sum energy is registered in full energy capture peaks no less than 1000 times. The use of numerical method to improve the resolution [7] decreases the width of such structures but increases the distortion of amplitude. Their form is unambiguously determined by the width of selected windows "effect+background" and "background" (Fig. 1), and also by their relative position. Undoubtedly, similar effect is always present in all spectra of traditional analysis of any γ–γ coincidences but there it is usually well masked. Rather accurate and entirely correct compensation of the corresponding distortions, without which it is impossible to obtain spectra of the type shown in Fig. 2, may be performed mathematically. To do this, the information on areas of the full energy peaks is required only at the registration of quanta with the energy

E_1 and E_2 for all cascades with greater sum energy (regardless of the isotope, from which they are emitted). This one or the procedure producing a similar effect is absolutely necessary when HPGe detectors are used with the efficiency 20% and more, basically, to reveal cascade peaks of the small intensity falling into the region of such structures.

Selection of parameters reproducing the corresponding structures in the specific part of the analyzed spectrum (of the type presented in Fig. 2), does not make problems: the minimization of sum of its negative values allows one to provide for quite a good numerical correction of the background under consideration. An example of the spectrum part containing sign-changing structures is given in Ref. [2] before and after a simple numerical correction carried out under the condition that its form changes weakly for the cascades with greater sum energy.

5. The contribution of ^{185}W

The main problem with possible contribution of other isotopes in the data of Table 1 is due to cascades of ^{185}W. This contribution manifests itself, first of all, in the sum amplitude of coinciding pulses from the cascades in ^{185}W overlapping the full energy capture peaks of ^{187}W. It manifests itself for the cascades with the sum energies 4685, 4652 and 4572 keV. The value J_f^π of the final levels of overlapping cascades equals to $1/2^-$ or $3/2^-$ for both isotopes. Accordingly, the ^{185}W contribution in the data of Table 1 may be mostly due to the comparable ratio of the number of captures and closeness of sum cascade intensities. Such overlapping requires the exclusion of well-resolved intense cascades belonging to ^{185}W from the data of Table 1 and a correction of sum intensities of Table 3.

The cascades excluded from Table 1 were taken to belong to ^{185}W in the case if within the limits of three standard errors of the energy of intermediate levels or γ transitions:

(a) intermediate levels of the corresponding energy were not observed in intensity distributions of ^{187}W with different sum energy or

(b) γ transitions of a close energy were detected as primary ones in the ^{185}W cascades.

Naturally, such a procedure does not guarantee a complete reliability of data in the Table 1. It is more likely that a selection of false levels would be made than for decay modes of excited levels of these nuclei. The set of intensities in question is determined with a rather high mean error ($\Delta E = 0.36$ keV) and this does not allow a more reliable exclusion of false cascades. There are no published data suitable for this procedure.

The maximum number of primary transitions belonging to ^{185}W (but included in Table 1) may be determined from the frequency distribution of energy differences of primary transitions in the compared nuclei. This analysis shows that there is no noticeable (overstepping the limits of statistical fluctuations) admixture of cascades from ^{185}W in the data in Table 1. The same is true for the statistically significant admixture of γ transitions from ^{183}W and from ^{184}W in the data in Table 1.

6. *Comparison with a known decay scheme*

Analysis of coincidences permits the identification of 386 two-step cascades belonging to 196 levels in ^{187}W up to the energy of $\simeq 3$ MeV. Of these, 100 levels are deexcited by two or more secondary γ transitions. Therefore, their existence with high confidence should be considered as most reliable. For the remaining 96 two-step cascades the sequence order of quanta could not be determined with the help of used algorithm [8]. The situation, when the primary transition has smaller energy than the secondary one, is quite possible for the excited states E_i higher than ~ 2 MeV. One should note that the neutron binding energy in ^{187}W equals 5467 keV.

Simple extrapolation of the number of excited levels decaying by 2, 3, 4, 5 secondary transitions (45, 29, 17 and 9, respectively) gives a probable estimation of the number of cascades with a low energy primary transitions is no more than 25.

This estimation, most likely, is overestimated since the average intensity of the $i_{\gamma\gamma}$ cascade per a given final level is approximately the same i.e. $3 - 3.5 \times 10^{-4}$ per capture for 1 or 2 secondary quanta. However, the value $i_{\gamma\gamma}$ increases significantly if the secondary transitions possess larger multiplicity. Therefore, one may assume that the number of observed cascades with the multiplicity 3 and 2 is restricted by the weakness of their primary transition at the present registration threshold. The energies of excited levels in ^{187}W presented in Table 1 have a confidence level of at least 90% of their total number under the asumption that possible unknown effects giving false spectroscopic information are absent. Consequently, the ^{187}W decay scheme above $\simeq 1$ MeV determined in the present experiment is the most reliable and rather complete. It can be compared with the current study of Bondarenko et al. [11].

7. *Estimation of sum intensity of two-step cascades of levels with the energy $E_f > 1$ MeV*

In the sum amplitudes of the spectrum of coinciding pulses a rather large number of two-step cascades to the final levels with the energy $E_f > 1$ MeV is observed, both in ^{187}W and ^{185}W. Due to very a bad peak/background ratio in this region of nuclear excitation, it is almost impossible to obtain detailed spectroscopic information (similar to that given in Table 1). However, these cascades contain very important information on the values of partial widths of secondary cascades of γ quanta to the excited levels of the complex nucleus. The direct experimental information of such type for heavy nuclei and energies of the decaying and excited levels higher than $1-2$ MeV is not available.

Certain opportunity to obtain an overall picture of this process may be extracted from estimation of the sum cascade yield with the various quantum multiplicity to final levels with $E_f > 1$ MeV. The solution of this problem in the general case was proposed for the first time in Ref. [3]. The part of population of high-lying levels caused only by two-step cascades may be determined from the comparison of areas of peaks of the sum spectrum for all values of E_f and for the values of cascade intensities for the lowest-lying levels presented in Table 3. It is necessary to take into account during the comparison that, on the one hand, areas of peaks of two-step cascades to the levels with $E_f > 1$ MeV increase due to an increase of efficiency of the cascade registration with smaller sum energy, and on the other hand, they decrease because a part of the energy of cascade γ transitions of decaying of any excited level may be registered by detectors and as a result will move an event from the full capture peak into the continuous distribution. (Probability of the simultaneous registration of three cascades in the full capture peaks is ~ 2 orders of magnitude smaller than the probability of the registration of a two-step cascade.)

The direct estimation of both values from experiment is difficult - an increasing amplitude of the "noise" line and sign-changing [2] structures lead to an increasing error of the determination of the efficiency of cascade registration average over the spectrum. The inevitable and unknown uncertainty of the real multiplicity of γ quanta of decaying of the level E_f by cascade γ transitions together with the uncertainty of necessary calculated data on the response function of detector for a γ quantum of the given energy $E_\gamma \leq 2$ MeV emitted by the target leads to an unknown error in the calculation of probability of registration by detectors of a part of energy of the third and subsequent cascade quanta. Therefore, it is better to perform estimation of the necessary correcting coefficients experimentally.

For this purpose values of average efficiency of registration of the cascades to the final levels lower than 1.9 MeV has been determined by simple linear extrapolation of average efficiency for the cascades to levels with $E_f < 0.5$ MeV.

The peak area reduction factor P_n in the spectrum of the sum amplitude of coinciding pulses due to the registration of any energy portion of the subsequent cascade transitions deexciting E_f levels has been determined experimentally. The fall-off of the efficiency of registration of single-escape and annihilation peaks captured by detectors in coincidences relative to the intensity i_1 of γ transition was determined in the independent experiment with the energy $E_\gamma = B_n - E_f$ for various peaks of the sum spectrum. Under the obvious assumption that for the ground state and the low-lying levels (decay quanta of which are absorbed by the Pb filters used in the experiment) $P_n = 1$, the experimental value P_n average over the interval ΔE_f, 0.5-1 MeV in width, varies with an increase of E_f ranging from 0.8 to 0.7 (with the relative error of no more than 25%). Simultaneously, this error includes both the error of determination of P_n caused by experimental conditions and by their real variations related to the variation of average multiplicity of γ quanta at the decay of excited state E_f. Very close P_n values have also been obtained for ^{185}W for $E_f < 2.2$ MeV, which may be regarded as an additional reliability demonstration in determining this value.

Here, it should noted, that earlier simulation [12] of the detection of the third and subsequent quanta of the cascade after decay of the excited state of even-even deformed nuclei gave a similar result. Their peak areas for levels with $E_f \sim 1$ MeV decrease at most by a factor of 1.3 due to the appearance of following quanta.

Possible intensity of two-step cascades per level with $E_f > 1$ MeV evaluated in the same way is presented in Fig. 3 in comparison with the calculation of their values using level densities and radiative widths of E1- and M1-transitions.

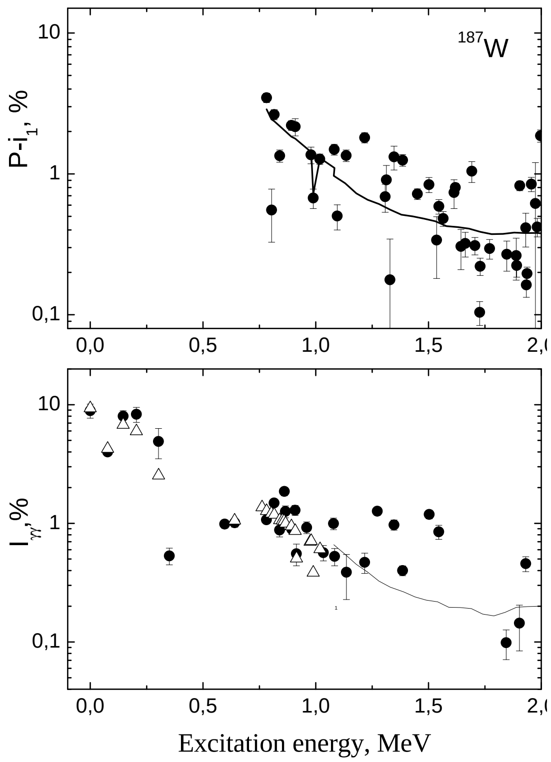

Fig. 3. Points with errors – the sum cascade population of intermediate levels of the two-step cascades (above). Intensities of the two-step cascades observed as resolved peaks in the spectrum of amplitude sums of coinciding pulses (below). Lines and triangles – their values calculated with the level density and radiative strength functions from Refs. [13, 14].

The latter accurately [15] reproduce the intensities of two-step cascades vs. energy of their primary transition, total radiative width of the neutron resonance and sum cascade population of levels of ^{187}W up to ≈ 3 MeV. Comparison of the calculated intensities and the experimental ones of two-step cascades higher than 0.5 MeV shows that their values determined according to the recent technique [15] do not provide for a detailed reproduction of experimental values for each individual level $E_f \leq 1.9$ MeV. At the same time, their sums coincide with good accuracy.

8. A possible regular structure of intermediate levels of the most intense cascades

According to the [16] theoretical models, the wave function of any excited state is determined by the coexistence and interaction of the fermion and boson excitations; for a deformed nucleus it is also determined by its rotation. At an increase of the excitation energy, the transition occurs from states with simple wave functions with few component types to mixed states (quasi-particles and phonons) with different degree of their fragmentation. It is necessary to study this process in all details experimentally. However, no methods for direct investigation of the structure of individual levels higher than several MeV in such heavy nuclei as ^{187}W, which could be adequate in solving the task, have been found so far.

Nevertheless, certain experimental information on a possible major components in the heavy deformed nucleus may also be obtained in this case. Authors of Ref. [17] have proposed an algorithm to search for regularities in the positions of intermediate levels of the most intensive cascades. For this purpose the autocorrelation function is calculated

$$A(T) = \sum_E F(E) * F(E+T) * F(E+2T) \tag{1}$$

where the intensities (given in Table 1) are shared by the Gaussian distribution $F(E) = \sum_E i_{\gamma\gamma} \times \exp(-0.5(\Delta E/\sigma)^2)$ with various thresholds of their selection. Such a distribution for the present data on the decay of ^{187}W excited states is presented in Fig. 4 for the value $\sigma = 25$ keV, and the autocorrelation functions for

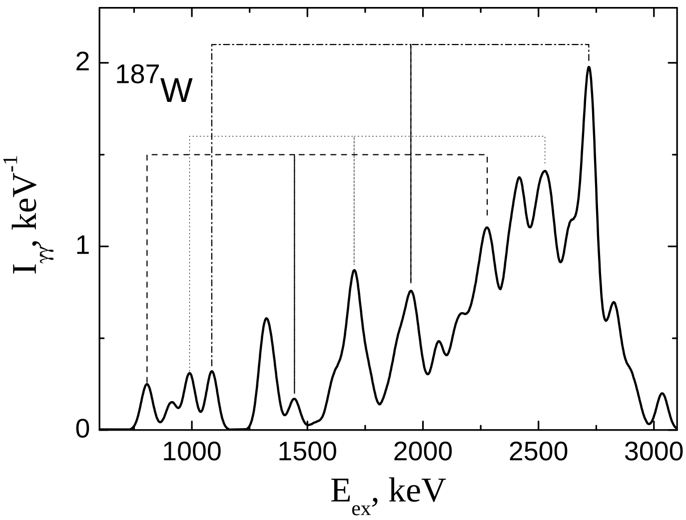

Fig. 4. Dependence of the "smoothed" cascade intensity from Table 1 on the energy of their intermediate level. Possible "bands" of almost harmonic excitations are marked. The parameter $\sigma = 25$ keV is used.

various thresholds – in Fig. 5. Unfortunately, the task to reveal regular character in the spectrum is distorted both by random variations of their amplitude and by positions and does not have a unique solution in the general case. For example, it is impossible to obtain [18] one unique value of the corresponding period T even for relatively small distortions from the spectrum made up of 25 "bands" with four almost equidistant intermediate levels. Greater values of T or the ones two times smaller are observed most frequently besides the initial ones. However, even in this situation the comparison of the found periods of equidistance in various nuclei depending on the number of paired nucleons in open shells points to the existence of their possible linear connection. The presence of levels with large components of the type with one phonon, two and more phonons at relatively high excitation energies follows from this fact. This assumption makes it possible to obtain a qualitative explanation of the reasons for discrepancy between the level density found experimentally and predictions of the model of non-interacting Fermi gas: the nuclear excitation energy is spent not only on the excitation of unpaired quasi-particles but also on the excitation of nuclear surface oscillations.

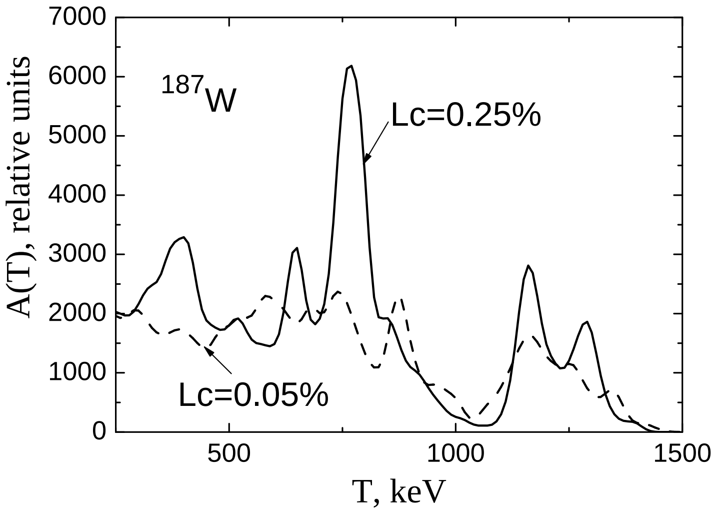

Fig. 5. Value of the functional $A(T)$ for the thresholds 0.05 and 0.25% of decays of the cascade intensities.

9. Conclusion

A detailed and very reliable scheme of excited levels and modes of their decay of the compound nucleus ^{187}W was obtained up to the excitation energy of ~ 3 MeV.

The results of comparison of the experimental and calculated cascade intensities in this nucleus, as in the earlier studied ones, point to the great need to modify the model representations of the properties of excited states of heavy nuclei. The existing discrepancy of the calculation and experiment may only be eliminated within the framework of a more accurate account of the existence and interaction of excitations of the fermion and boson type. Otherwise, it would be impossible to achieve a reasonable agreement (within the experimental accuracy) of the calculated parameters and of the experimental values. In particular, this refers to neutron capture cross sections for the neutron energy lower than several MeV and spectra of the emitted γ quanta.

References

[1] M. P. Beitins et al., Z. Phys. A - Hadrons & Nuclei **341** (1992) 155.

[2] V. A. Bondarenko et al., Fizika B (Zagreb) **11**, 4 (2002) 201.

[3] V. A. Bondarenko et al., in XII Int. Sem. Interactions of Neutrons with Nuclei, Dubna, May 2004, E3-2004-169, Dubna (2004) 38; http://arXiv.org/abs/nucl-ex/0406030.

[4] J. Honzátko et al., Nucl. Instr. and Meth. A **376** (1996) 434.

[5] S. J. Friesenhanh, E. Haadad, F. H. Frohner and W. M. Lopez, Nucl. Science Eng. **26** (1966) 487.

[6] S. T. Boneva, E. V. Vasilieva, Yu. P. Popov, A. M. Sukhovoj and V. A. Khitrov, Sov. J. Part. Nucl. **22**, 2 (1991) 232; S. T. Boneva et al., Part. Nucl. **22**, 6 (1991) 698.

[7] A. M. Sukhovoj and V. A. Khitrov, Instrum. Exp. Tech. **27** (1984) 1071.

[8] Yu. P. Popov, A. M. Sukhovoj, V. A. Khitrov and Yu. S. Yazvitsky, Izv. AN SSSR, Ser. Fiz., **48** (1984) 891.

[9] E. V. Vasilieva et al., Bull. Russian Academy of Science, Physics, **57** (1993) 1582.

[10] V. A. Bondarenko et al., Nucl. Phys. A **619** (1997) 1.

[11] V. A. Bondarenko et al., Nucl. Phys. A **811** (2008) 28.

[12] I. Tomandl, Doctoral thesis, Řež (1999).

[13] W. Dilg, W. Schantl, H. Vonach and M. Uhl, Nucl. Phys. A **217** (1973) 269.

[14] P. Axel, Phys. Rev. **126** (1962) 683; J. M. Blatt, V. F. Weisskopf, *Theoretical Nuclear Physics*, Wiley, New York (1952).

[15] E. V. Vasilieva, A. M. Sukhovoj, V. A. Khitrov, Phys. At. Nucl. **64**, 2 (2001) 153; http://arXiv.org/abs/nucl-ex/0110017; A. M. Sukhovoj, V. A. Khitrov, Phys. Part. Nucl. **36**, 4 (2005) 359.

[16] L. A. Malov and V. G. Soloviev, Yad. Fiz. **26**, 4 (1977) 729.

[17] A. M. Sukhovoj and V. A. Khitrov, Izv. RAN, Ser. Fiz., **61**, 11 (1997) 2068.

[18] E. V. Vasilieva et al., Izv. AN SSSR, Ser. Fiz., **57**, 9 (1993) 118.

DVOFOTONSKE KASKADE U γ RASPADU SLOŽENE JEZGRE ^{187}W

Proučavamo dvofotonske kaskade iz reakcije ^{186}W(n,2γ)^{187}W mjerenjem $\gamma-\gamma$ koincidencija izvedenih u Řežu. Odredili smo njihove ukupne intenzitete u odnosu na konačno stanje dosegnuto kaskadom u području energije $\approx$ 1.9 MeV. Procesi kaskadnih raspada u ovoj jezgri, kao i u sličnim ranijim mjerenjima, ne mogu se opisati ako se ne uzme u obzir nuklearna struktura na energijama nižim od barem polovice energije vezanja neutrona. Odredili smo shemu raspada ^{187}W, uključivši 386 kaskada do energije uzbude $\sim$ 3 MeV. Shema sadrži 196 viših stanja te jezgre, a najvjerojatniji spinovi tih stanja su 1/2 i 3/2. Kao i u ranijim proučavanjima, popunjavanje međustanja najintenzivnijim kaskadama možda ukazuje na njihova harmonijska svojstva.