ISSN 1330–0016
CODEN FIZBE7

A SEARCH FOR THE γ-DECAY OF THE ^{168}Er COMPOUND NUCLEUS IN THE $(n, 2\gamma)$ REACTION

EVGENY P. GRIGORIEV[a], VALERY. A. KHITROV[b], ANATOLY. M. SUKHOVOJ[b] and ELLA V. VASILIEVA[b]

[a] *Research Institute of Physics, St.-Peterburg State University, Russia*

[b] *Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia*

Received 28 May 1999; revised manuscript received 27 June 2000
Accepted 4 September 2000

The information derived from the spectra of two-step γ-cascades proceeding between the compound state of ^{168}Er and its low-lying ($E_f < 1.1$ MeV) levels is analysed. The data on the most intensive cascades resolved experimentally were used to verify and make more precise the already known decay scheme of this nucleus and to extend it to higher excitation energies. The degree of its completeness was estimated numerically for a decay scheme of 91 levels with $E_{ex} < 3.14$ MeV. Total intensities of all cascades (including those unresolved experimentally which form continuous parts of the experimental spectra) were used for testing the models which attempt to explain and describe the cascade γ-decay process in the excitation energy diapason up to the neutron binding energy B_n.

PACS numbers: 25.40.LW, 27.70.+q UDC 539.172.4

Keywords: ^{168}Er compound state, two-step γ-cascades, low-lying ($E_f < 1.1$ MeV) levels, total intensities

1. *Introduction*

The structure of the ^{168}Er even-even deformed nucleus has been well studied in complex experiments [1,2]. Excited states of this nucleus were studied in different nuclear processes, first of all by the (n, γ) reaction using the best apparatus of 1980 – 1990s, the magnetic β-spectrometers, and semiconductor and crystal-diffraction γ-spectrometers. In this reaction, the spectrum of γ-transitions was measured for the intervals $E_\gamma < 2.52$ keV and $4.62 < E_\gamma < 7.7$ MeV (B_n=7.771 MeV). The experimental data allowed the authors of Refs. [1] and [2] to establish the levels of this nucleus (probably partially) up to the excitation energy of 3.14 MeV and the complete decay scheme up to $E_{ex} < 2.6$ MeV. The parameters of more than 30 rotational bands were also determined.

Further experiments, however, have shown that real situation in ^{168}Er differs from these results. Recent measurements of the $\gamma\gamma$-coincidences in the (n,γ) reaction [3,4] stipulated the necessity of introducing a number of new excited levels of ^{168}Er in the diapason from 2.19 to 2.97 MeV. It was shown that a number of γ-transitions cannot depopulate the levels to which they were assigned in accordance with the combinatorial rule. The data on the $(n,n'\gamma)$ reaction [5] have shown that three levels, at 2133 keV ($J^\pi = 1^+$), 2177 keV (2^+) and 2365 keV (1), were introduced by mistake. Authors of Ref. [5] made the depopulation of some other states more precise and showed that the mechanism of the $(n,n'\gamma)$ reaction corresponds to the predictions of the statistical model.

The most recent theoretical analysis of the structure of ^{168}Er was made by V. G. Soloviev et al. [6]. The analysis used all available experimental data and, probably, exhausted their value from the point of view of verification and modification of nuclear models (at least with respect to the so well studied [7] nucleus as ^{168}Er). The analysis resulted in the two conclusions which were important for our experiment:

(a) The probabilities of γ-transitions between excited levels are rather strongly affected by small admixtures in the wave functions of these states.

(b) For a better understanding of the properties of heavy deformed nucleus, it is necessary to extend the interval of excitation energy up to ≈ 4 MeV.

One can conclude that the possibility of obtaining new information on ^{168}Er below 2.5 MeV was practically exhausted, also due to the impossibility of precise calculation of the wave functions of the low-lying states. New data, however, can be obtained using new methods for the study of the deformed nucleus in the region of high level density. Another important conclusion [6] is that the structure of the states should become complicated at higher energy due to the presence, e.g., of two-phonon and other components in their wave functions. It was pointed in Ref. [8], the wave function of the neutron resonance contains $\approx 10^9$ components, from the two-quasiparticle and single-phonon (even nucleus) to the many-quasiparticle and many-phonon components. The way of extracting information on nuclear structure in the region of the transition from the simple levels to these compound states is rather difficult but perspective work.

It is clear that theory cannot describe the structure of individual levels at high excitation and, as repeatedly underlined by V. G. Soloviev, from the experiment, one should extract the data on the nuclear properties averaged over some energy interval. These can be the density of levels $\rho(J^\pi, E_{ex})$ and the mean probabilities of their population after the decay of the compound state. The method suggested by us for the study of any nucleus is mainly aimed to solve this problem but it also gives the information on the low-lying levels. The latter is important from the point of view of estimation of the correctness and reliability of conclusions concerning the excitation region above 2-3 MeV.

The experimental study of the two-step γ-cascades and analysis of spectroscopic information performed by us allowed a verification of the known decay scheme of ^{168}Er and its extention above the excitation energy of 2.5 MeV. The use of the method of Ref. [9] of analysis of the spectroscopic data on (n, γ) and $(n, 2\gamma)$ reactions (i.e., of the data obtained in single-detector measurements and in two-detector sum-coincidence measurements) allowed some important conclusions to be made about:

(a) the presence of unresolved doublets of levels and transitions, and

(b) the degree of completeness of a set of transitions depopulating a given level.

2. *Experiment and data analysis*

The methods of measurements and data analysis of the "$(n, 2\gamma)$ reaction" (as named below) are described in detail in Refs. [10] and [11]. The distinctions from the traditional analysis of the $\gamma - \gamma$ coincidences are the following:

(a) From the mass of coinciding pairs of γ-transitions, only those whose sum energies exceed a sufficiently high value are selected and accumulated for further analysis. In the present experiment, this threshold was set at 5 MeV and, to reject annihilation quanta, the detection threshold for each transition was set at 520 keV;

(b) The spectra are formed from events satisfying the condition $B_n - E_f - \delta < E_1 + E_2 < B_n - E_f + \delta$. The widths and positions of the corresponding intervals 2δ are unambiguously determined from the sum-coincidence spectrum. In the other words, from the three-dimensional space "number of events - E_1 - E_2", if using traditional analysis, one selects the coincidences within the "corridor" that is parallel to one of the energy axes, but the method used by us uses the same data along the diagonal $E_1 = (B_n - E_f) - E_2$. This allows:

(1) to select events from the region of the three-dimensional space which is characterized by a minimal possible background;

(2) to use numerical method [12] for improving the energy resolution without decreasing the efficiency of registration;

(3) to subtract the background from the spectra in an effective and reliable way, built in an "off-line" regime;

(4) to concentrate a maximum number of peaks of cascade transitions into a minimum number of spectra at fixed both initial and final cascade levels, and to distinguish the continuous components of spectra, which are related to a great number of low-intensity cascades;

(5) using the maximum likelihood method, to determine [13] unambiguously and independently the quanta ordering in a majority of the observed intense cascades of dipole transitions with the sum energy of several MeV. Other experimental techniques allow such a direct determination in very rare cases.

The experiment was performed at the IBR-30 pulsed reactor in Dubna. The $\gamma\gamma$-coincidences were registered by a system of two 7 – 10% efficiency Ge(Li) detectors for about 500 hours. The advantages of the method mentioned above permitted to obtain information which is not less than that accumulated by authors of Ref.

[4] by means of a TESSA array using 16 Compton-supressing Ge detectors over a 4-day period at the neutron beam of the BNL reactor.

3. *Experimental results*

3.1. Decay scheme

The bulk of information on cascade γ-transitions obtained with the sum coincidence technique is limited, first, by the background conditions which are related to the registration of events by Ge detectors in a continuous distribution but not in full energy peaks. For this reason, it was possible to obtain only the spectra of two-step cascades proceeding between the compound state and the following low-lying levels of ^{168}Er: 79.80 keV (2^+), 264.09 keV (4^+), 548.75 keV (6^+), 821.17 keV (2^+_γ), 895.80 keV (3^+_γ), 994.75 keV (4^+_γ), and 1094.04 keV (4^-), i.e., the spectra of cascades terminating at the three levels of the rotational band of the ground state, three levels of the γ-band, and the head level of the band $K^\pi = 4^-$.

The energies of these levels and the value $B_n = 7771.15$ keV were used for calibrating the energy scale. The absolute intensities (in % per decay) of all cascades were determined with the help of a normalization of the relative intensities of the strongest cascades to their absolute values $i_{\gamma\gamma}$, which were calculated using the equation

$$i_{\gamma\gamma} = i_1 \times BR. \tag{1}$$

The absolute intensities i_1 of the corresponding primary transitions were obtained using their relative values from Ref. [1,2] and the normalizing multiplier 0.02 from Ref. [3]; the branching ratios $BR = i_2/\sum i_2$ were determined in a standard way from the spectra of secondary transitions coinciding with the same set of primary transitions. To obtain the BR values, we used all the mass of coincidences registered in the present experiment. The total intensity of all two-step cascades observed in the experiment (including those unresolved experimentally) is equal 37(4)%.

The mean error in the determination of energies of the cascade transitions was about 1.55 keV. For this reason, in Tables 1 and 2, which summarize the information on the decay scheme of ^{168}Er accumulated by us, the energies of the secondary transitions determined in the present experiment are replaced by more precise data [1]. According to Ref. [9], this was performed by accounting not only for the differences between the transition energies obtained by us and authors of Ref. [1], but also for the relations between the intensities of cascades and their low-energy secondary transitions. One must test these relations for two reasons. First, to permit the control of correctness of the assignment of the energy values. Second, to provide an opportunity to verify the data of Ref. [1] in order to reveal the doublets of unresolved transitions. If the ratios $r = i_{\gamma\gamma}/i_2$ for the cascades proceeding via the same intermediate level are in agreement within the experimental errors, then one can conclude that transition chosen from the data of Ref. [1] is the one that depopulates a given level and that it is not a doublet. It is obvious that the cascade intensity must not exceed the intensities of the corresponding primary and secondary transitions from Ref. [1] which are compared to those obtained by us.

TABLE 1. A list of absolute intensities (per 10^4 decays), $i_{\gamma\gamma}$, of measured two-step cascades and energies, E_2, of their secondary transitions for ^{168}Er. i_1 and i_2 are relative intensities of primary and secondary cascade transitions according to Refs. [1] and [2], respectively. E_i is the energy of intermediate level with $J^\pi K$. J_f is the spin of the final state of cascade transitions.

E_i (keV)	$J^\pi K$	J_f	E_1 (keV)	E_2 (keV)	$i_{\gamma\gamma}$	i_1	i_2	$i_{\gamma\gamma}/i_1$ (%)	$i_{\gamma\gamma}/i_2$ (%)
821.17	2^+2	2	6950.2	741.36	2.8(5)	4.4	491	64(15)	0.6(2)
895.79	3^+2	2	6875.3	815.99	2.5(4)	1.2	3000	200(40)	0.08(2)
994.75	4^+2	4	6776.6	730.66	1.8(4)	1.6	831	112(30)	0.22(5)
1117.57	5^+2	4	6663.5	853.47	1.3(4)	1.0	518	130(40)	0.25(9)
1193.03	5^-4	4	6578.4	928.94	1.8(5)	22	110	8(3)	1.6(5)
1276.27	2^+0	2	6495.1	1196.51	1.9(5)	7.6	52	25(8)	3.7(10)
		4		1012.19	2.9(5)		99	38(7)	2.9(5)
1403.74	2^-1	2	6367.42	1323.91	10.5(11)	14.6	124	72(8)	8.5(8)
		2γ		582.57	2.1(8)		37	14(8)	5.7(24)
1411.10	4^+0	2	6360.4	1331.32	-	18.4	112	-	-
		4		1147.00	-		74	-	-
		3γ		862.36	2.7(8)	-	72	15(6)	3.8(11)
1431.47	3^-1	2	6339.9	1351.54	2.4(6)	3.8	133	63(16)	1.7(5)
		4		1167.40	1.3(6)		130	34(17)	1.0(5)
1493.14	2^+0	4	6278.2	1229.08	1.3(6)	0.7	41	180(90)	3.2(15)
1541.56	3^-3	4	6229.7	1277.45	< 4.2	40	16	-	< 30
		2γ		720.39	6.5(11)		110	> 16	6(1)
		3γ		645.78	< 4.6		35	-	< 0.13
		4γ		546.80	< 3.3		23	-	< 0.14
1541.71	4^-1	4	6229.7	1277.59	< 4.2	40	141	-	< 0.03
		3γ		645.94	< 4.6		24	-	< 0.2
		4γ		546.96	< 3.3		40	-	< 0.1
1569.45	2^-2	2γ	6202.1	748.28	4.7(14)	10.4	86	45(14)	0.054(20)
		3γ		673.67	4.0(13)		38	38(13)	0.10(3)
1574.12	5^-1	4	6197.42	1310.03	8.6(9)	13.8	123	62(7)	0.070(7)
		6		1025.38	5.8(11)		70	42(4)	0.083(16)
1615.34	4^-3	3γ	6155.8	719.55	-	21.6	78	-	-
1633.46	3^-2	2γ	6137.8	812.29	< 23	38.8	69	< 60	< 0.3
		3γ		737.69	< 31	-	82	< 80	< 37
		$4\ \gamma$		638.71	9(2)	-	55	< 80	0.16(4)
1656.27	4^+0	2	D: 6116.9+	1576.58	1.0(4)	6.4	< 6	16(7)	> 0.17
		4	6113.5	1392.21	1.5(5)		98	23(6)	0.015(5)
1719.18	4^-2	3γ	6151.96	823.39	< 40	30.2	85	< 130	< 0.9
		4γ		724.43	< 10		33	< 30	< 0.3
1736.68	4^+3	4γ	6034.7	741	5.1(16)	5.8	<491	88(28)	> 1
1828.06	3^-3	3γ	5943.3	932.27	8.4(20)	13.5	51	62(13)	16(4)
		4γ		833.29	4(1)		32	30(8)	13(4)
1892.94	4^-3	4^-	5878.34	798.89	50(3)	54	160	93(6)	31(2)
1905.09	4^-4	4^-	5866.4	811.04	< 30	10.9	115	< 300	< 30
1913.90	3^-0	2	5857.6	1834.05	< 8.6	19.8	40	< 43	< 43
		4		1649.77	6.9(19)		50	35(10)	14(5)

Table 1 (continued)

E_i (keV)	$J^\pi K$	J_f	E_1 (keV)	E_2 (keV)	$i_{\gamma\gamma}$	i_1	i_2	$i_{\gamma\gamma}/i_1$ (%)	$i_{\gamma\gamma}/i_2$ (%)
1915.50	3^+2	2	5857.6	1835.68	< 8.6	19.8	58	< 43	< 15
		2γ		1094.4	1.7(6)		12	8.5(30)	14(5)
		4γ		920.78	4.6(9)		14	23(5)	33(7)
1930.39	2^+2	2	5841.2	1850.46	1.4(5)	1.2	22	116(50)	6(2)
1972.93	2^-1	2	5799.2	1892.73	1.5(5)	2.6	30	58(20)	5(2)
1994.82	3^+2	2	5777.6	1914.97	3.1(6)	23	40	13(3)	8(2)
		4		1730.89	2.2(7)		18	10(3)	12(4)
2022.33	3^-3	2	5748.8	1942.69	8.4(9)	11.1	64	76(8)	13(2)
		4		1758.47	2.0(7)		18	18(7)	7(2)
		4^-		928.29	5.0(2)		110	45(2)	5(2)
2031.09	4^+0	4	5740.3	1766.99	1.3(5)	2.2	42	59(23)	3(1)
2059.98	4^-4	4^-	5711.4	965.94	7.4(18)	10.5	65	70(20)	11(2)
2088.42	4^-3	4	5682.0	1825	1.8(9)	7.6	-	24(12)	-
		4γ		1093.67	1.8(9)		5	24(12)	36(20)
2097.57	4^-1	4	5673.7	1833.43	6.2(12)	25.2	38	25(5)	16(3)
		3γ		1201.76	8.5(17)		26	34(7)	33(7)
2129.24	5^-0	4	5642.0	1865.10	9.7(11)	13.5	40	72(8)	24(3)
		6		1580.72	7.4(14)		38	55(11)	19(4)
2148.37	5^-4	4	5623.1	1883.47	2.2(7)	11.5	7	19(7)	31(10)
2188.38	4^+	6	5585.7	1639.73	5.1(13)	5.2	7	100(20)	73(19)
2200.42	5^-3	4	5571.0	1936.4	2.0(7)	14.1	< 30	14(5)	> 66
		6		1651.5	4.3(11)		< 7	30(8)	> 61
2238.18	4^+4	4^-	5533.2	1144.11	4.5(18)	5.3	59	85(4)	8(3)
2262.70	3^-3	2γ	5508.6	1441.41	1.5(7)	9.3	19	16(8)	8(4)
		3γ		1366.91	3.9(13)		23	42(15)	17(6)
2267.62	5^+	4^-	5503.6	1173.56	8.4(23)	8.9	47	94(26)	18(5)
2302.68	3^-	2	5468.8	1481.71	2.2(7)	10.4	10	21(8)	22(8)
		4γ		1309	3.3(10)		< 123	32(11)	> 27
2311.07	4^+	4	5460.2	2047.03	4.7(10)	5.8	47	81(19)	10(2)
2336.26	4^+	3γ	5434.3	1440.41	< 4.1	15.3	10	< 27	< 40
		4γ		1341.58	3.8(9)		11	25(7)	35(6)
2337.13	3^-	2	5434.3	2256.7	1.2(5)	15.3	17	8(3)	7(3)
		2γ		1515.98	3.0(8)		< 20	20(6)	> 15
		3γ		1441.42	< 4.1		< 15	< 27	-
2365.17	5^-5	4^-	5405.9	1271.13	14(3)	12.0	29	117(30)	48(10)
2392.63	4^-2	4γ	5378.7	1398.05	5.2(13)	11.7	12	44(12)	43(12)
		4^-		1298.40	< 10		7.2	< 85	< 140
2393.63	2^+	2	5378.7	2314.49	1.3(6)	11.7	14	11(6)	9(5)
2398.55	(5)	6	5373.2	1850	7.1(24)	12.7	< 22	56(20)	> 32
		4^-		1302	< 10		-	< 80	-
2402.38	4^-	3γ	5369.2	1506.49	15(3)	20	18	75(25)	83(20)
		4γ		1407.67	5.8(11)		7	29(5)	83(17)
		4^-		1308	7.2(20)		< 120	36(10)	> 6
2411.64	4^-	2	5359.7	2147.34	1.1(5)	48	< 7.2	23(11)	> 15
		3γ		1515.98	23(8)		51	48(16)	45(17)
		4γ		1417.05	4.3(11)		5 of 15	9(3)	~ 86
		4^-		1317.56	< 19		5	< 40	< 38
2423.24	4	4	5348.1	2159.15	7.1(10)	6.7	35	106(15)	20(3)
2437.13		4	5336.7	2137.04	2.0(7)	1.6	-	125(40)	-
2451.18		4^-	5320.5	1358	4.6(20)	5.4	< 10	85(40)	> 46
2477.13	5^-	6	5295.8	1928.21	12(2)	42	16	29(5)	75(20)
2478.09	3^-	2	5292.6	2398.25	1.5(5)	42	< 18	4(2)	> 8
		4		2214.47	8.9(12)		13	21(4)	68(10)

Table 1 (continued)

E_i (keV)	$J^\pi K$	J_f	E_1 (keV)	E_2 (keV)	$i_{\gamma\gamma}$	i_1	i_2	$i_{\gamma\gamma}/i_1$ (%)	$i_{\gamma\gamma}/i_2$ (%)
2478.09		2γ		1656.84	5.4(9)		< 8	13(3)	> 68
		3γ		1582.96	9.4(19)		9	22(5)	100(20)
		4γ		1484.46	10.2(15)		17	24(4)	60(10)
2494.02	(3^-)	2	5277.4	2414.33	3.1(7)	11.6	8	27(7)	39(10)
		4		2229.27	2.5(8)	-	5	22(8)	50(17)
		2γ		1672.84	5.0(8)		19	43(8)	26(4)
2513.70	(5^-)	4γ	5258.6	1518.95	2.2(8)	12.7	9	17(7)	24(9)
2528.69	$(3\text{-}5)^-$	4γ	5242.5	1534.05	6.5(11)	13.2	21	49(8)	31(6)
2551.5		4γ	5218.7	1556.84	4.4(18)	6.9	27	64(30)	16(7)
2559.6	(5^-)	4γ	5212.5	1563.85	4.6(17)	19.3	15	24(8)	31(12)
2571.3		3γ	5200.0	1675.49	3.9(14)	9.7	20	40(15)	20(7)
		4γ		1576.58	4.0(14)		< 6	41(15)	> 67
2601.5		2	5169.9	2522	12(2)	36	-	33(6)	-
		4		2337.1	13(2)		16	36(6)	81(12)
		6		2052	3.6(12)		-	10(3)	-
2629.5		4	5141.8	2365.30	1.8(7)	5.8	13	31(12)	14(5)
2656.7	(3^-)	2γ	5114.6	1835.68	8.2(10)	14.5	< 58	57(7)	> 14
		3γ		1762.19	9.6(22)	-	< 13	66(15)	> 74
2659.8	(3^-)	2	5111.5	2580	4.8(8)	19.1	-	25(4)	-
		4		2395	2.1(8)		-	11(4)	-
		3γ		1765.02	6.1(15)		10	32(8)	61(15)
		4γ		1665.74	5.4(11)		8	28(6)	68(14)
2673.6		4	5097.7	2410	3.8(9)	5.4	< 14	70(17)	> 27
2683.5		4	5087.6	2420	4.5(8)	4.8	< 16	94(17)	> 28
2700.5		4	5070.8	2436.49	6.3(10)	15.9	15	40(6)	42(7)
2733.4	$(3,4^-)$	4	5038.2	2469	4.7(18)	24	-	20(8)	-
		3γ		1837	8.4(19)		-	35(8)	-
2739.1	$(3,4^-)$	4	5032.2	2475	1.9(6)	12	15	16(5)	13(4)
2746.5		2γ	5024.8	1925	2.0(6)	2.6	< 20	77(23)	> 10
2769.58		4^-	5001.6	1675.49	7.2(20)	12.5	20	58(16)	36(10)
2777.5	(5^-)	6	4993.8	2229.27	4.1(14)	6.0	5	68(23)	82(28)
2786.9	$(3,4^-)$	4	4984.5	2524.0	7.5(12)	14.7	< 28	51(8)	> 27
		3γ		1890.9	7.5(13)		4	51(9)	187(33)
2790.8		4	4980.5	2524	7.5(13)	4.2	8	178(31)	94(16)
2810.9		4	4960.4	2547	3.1(8)	3.3	-	94(24)	-
2819.7		4	4951.7	2556	4.0(10)	2.2	-	181(45)	-
2849.8		2	4921.6	2770	2.5(10)	46	-	5.4(21)	-
		4		2586	5.3(10)		-	11(2)	-
		6		2300.63	26(3)		34	57(7)	76(9)
		2γ		2029	3.3(8)		< 7	7(2)	> 47
		3γ		1954	5.5(18)		< 6	12(4)	> 92
		4γ		1855.6	4.8(12)		3	10(3)	160(40)
		4^-		1756	8(2)		< 10	17(4)	> 80
2875.2	4^-	4	4896.4	2611	3.8(10)	12.7	-	30(8)	-
		4γ		1880.47	3		3	-	-
2890.2		6	4881.1	2341.89	5.0(15)	4.4	12	114(34)	42(13)
2895.4		2	4875.9	2815	2.8(9)	3.9	-	72(23)	72(23)
		4		2631	2.8(9)		-	72(23)	-
2920.0		4	4851.4	2656	3.6(10)	5.0	-	22(20)	-
2933.2	(3^-)	2	4838.1	2853	2.7(12)	8.6	-	31(14)	-
		4		2669	5.0(10)		-	58(12)	-
		4γ		1938.69	4.5(14)	-	10	52(16)	45(14)
		4^-		1839	13.0(25)		< 20	151(29)	> 26

Table 1 (continued)

E_i (keV)	$J^\pi K$	J_f	E_1 (keV)	E_2 (keV)	$i_{\gamma\gamma}$	i_1	i_2	$i_{\gamma\gamma}/i_1$ (%)	$i_{\gamma\gamma}/i_2$ (%)
2950.0		2	4820.7	2820	3.2(12)	4.2	-	76(28)	-
		4		2686	4.1(10)		-	-	-
2969.6	(5^-)	6	4801.7	2420	2.9(13)	20.4	< 16	14(7)	> 8
2972.6		2	4798.8	2893	2.8(10)	2.9	-	97(30)	-
2979.3		2γ	4792.1	2158	2.9(10)	3.9	< 10	74(25)	> 30
2991.3	(3^-)	2	4780.0	2911	3.2(10)	10	-	32(10)	-
2998.2		4	4773.2	2734	3.2(10)	7	-	46(16)	-
3011.8		2	4759.5	2932	5.0(12)	10.5	-	48(11)	-
		4		2747	6.9(12)		-	-	-
		6		2462	8.6(17)		-	-	-
		2γ		2189	2.4(10)		< 5	-	> 48
3026.0	(5^-)	6	4745.4	2472.2	14.9(21)	18	15	83(12)	100(20)
3030.5		4	4740.9	2769	3.8(9)	5.4	-	70(17)	-
3033.8		2γ	4737.6	2212.7	3.3(11)	2.6	8	127(42)	41(14)
3042.1		4^-	4729.2	1948.72	2.8(11)	3.6	4	78(30)	70(28)
3049.6		2	4721.7	2970	3.4(12)	6.8	-	50(18)	-
		2γ		2229.27	2.7(10)		5	37(15)	54(20)
3068.8		6	4702.5	2520	6.1(16)	5.4	-	113(30)	-
3082.8		2	4688.5	3003	3.2(12)	10.2	-	31(12)	-
		4		2819	4.3(15)		-	42(15)	-
		6		2533	2.6(15)		-	25(15)	-
3099.42	(3^-)	2γ	4671.4	2277.97	-	13.5	6	-	-
		3γ		2203.65	-		19	-	-
		4γ		2104.67	5.3(13)		8	39(10)	66(16)
3111.25	(3^-)	2	4660.0	3031	3.3(9)	13.5	-	24(7)	-
		2γ		2290	4.2(11)		< 5	31(8)	> 84
		3γ		2214.47	8(3)		< 13	59(22)	> 61
		4γ		2116.48	4.1(14)		9	30(10)	45(16)
3118.2		4	4653.2	2860	7(3)	16.9	-	43(18)	-
3124.0		6	4674.4	2575	13(8)	12.4	-	105(65)	-
		2γ		2303.22	6.5(13)		12	52(10)	54(11)
3127.9	(5^-)	4	4643.4	2864	11(3)	23.8	-	46(13)	-
		6		2579	6.7(8)		-	28(4)	-
3142.7	(3^-)	2	4628.7	3063	2.0(9)	14.6	-	14(6)	-
		4		2879	3.7(14)		-	25(10)	-

"$<$" denotes intensities of transitions and cascades in the case of unresolved doublet (for the cascade — at presence of unresolved doublet of primary transitions or due to the possible registration of its primary and secondary quanta); the intensity of unresolved primary transition is given for revealed doublets of close levels.

If this is not the case, then either the intensity of the high-energy transition from Ref. [1] was determined with an error, or, for some reason, the data on energies and intensities of cascades obtained by us contain an error. Potential errors in our data, however, can be due to one possibility only: the energy of the secondary quantum in the cascade of three and more γ-transitions coincides with the difference of the energies of a pair of lower-lying levels to a precision of 3 – 4 keV, and this (i.e., third) transition must be dominant in the γ-decay of the intermediate level excited by the preceding transition. Such a situation seems to occur for the cascades with the 1633 and 1905 keV intermediate levels. However, we cannot explain, in the same way, the surplus in the intensities of the cascades proceeding through the 895, 1995, and 3011 keV intermediate levels. This discrepancy requires another explanation. One cannot exclude, for example, the possible influence of interference effects on the intensity of primary transitions, since the effective energy of captured neutrons in different experiments can be different. The most probable explanation is that, due to poor statistics, we observed a random divergence in our experiment which is several times larger than the statistical error.

TABLE 2. Absolute intensities (per 10^4 decays of the ^{168}Er compound nucleus) of the two-step cascades. E_1 is the energy of the primary cascade transition exciting intermediate level at the energy E_i. J_f is the spin of the final state of cascade.

E_1 (keV)	E_i (keV)	J_f	$i_{\gamma\gamma}$	E_1 (keV)	E_i (keV)	J_f	$i_{\gamma\gamma}$
5958.8	1812.2	2γ, 3γ, 4γ	22(3)	4257.5	3513.5	6	8(2)
5552.8	2218.2	3γ	5.7(17)	4250.3	3520.7	2	2.4(8)
5055.3	2715.7	2, 4	5.6(12)	4211.4	3559.6	6	5(2)
4619.5	3151.5	2γ	3.4(1)	4200.5	3570.5	6, 2γ,3γ	15.(3)
4613.1	3157.9	2	2.6(8)	4183.4	3587.6	4γ	3.7(14)
4573.4	3197.6	2	4.3(9)	4164.6	3606.4	2	1.7(8)
4566.2	3204.8	4	6.1(14)	4153.6	3617.4	2, 2γ, 4γ	9(2)
4548.2	3222.8	4, 6, 2γ	14(3)	4128.3	3642.7	2γ	3(1))
4533.4	3237.6	4	4.1(14)	4110.5	3660.5	2γ	4(1)
4486.3	3284.7	2, 4, 6	14(3)	4091.3	3679.7	2γ, 4γ	8(2)
4444.1	3326.9	2	3.2(8)	4068.9	3702.1	2	1.7(8)
4436.4	3334.6	6, 3γ	12(3)	4056.2	3714.8	3γ	7(2)
4423.7	3347.3	4γ	5.0(15	4032.4	3738.6	2γ, 4^-	11(3)
4394.8	3376.2	2, 6, 2γ	12(2))	4016.0	3755.0	3γ	9(2)
4376.9	3394.1	4^-	7(2)	4009.8	3761.2	2γ	4(1)
4372.1	3398.9	2	3.0(8)	3989.7	3781.3	4, 6, 4γ	16(3)
4355.9	3415.1	2	3.3(8)	3972.0	3799.0	6	4.3(18)
4339.4	3431.6	2, 6	7(2)	3954.4	3816.6	2γ	3.6(14)
4295.7	3475.3	2	3.6(8))	3936.2	3834.8	4	3(1)
4284.1	3486.9	3γ	6(2)	3883.0	3888.0	3γ	7(2)
4275.0	3496.0	2, 6	10(2)	3876.2	3894.8	4	5(1)
4272.1	3498.9	4^-	9(3)	3863.1	3907.9	4	4(1)
4263.6	3507.4	2	3(1)	—	—	—	—

The distribution of the ratios of the sum cascade intensities to the intensity of their common primary transition $r = \sum i_{\gamma\gamma}/i_1$ is shown in Fig. 1. The mean value with respect to 91 intermediate cascade levels is $< r >= 0.83$. This means that the sum intensity of the secondary transitions listed in Table 1 amounts to 83% of their total value. The remaining 17% are related to the cascades with $i_{\gamma\gamma} \leq 10^{-4}$ terminating at the 7 levels mentioned at the beginning of this paragraph or to cascades to the ground state or to levels at $E_f > 1.1$ MeV. Figure 1 and Table 1 determine quite unambiguously those states of ^{168}Er whose decay modes were established incompletely. Certainly, the value of r is affected by the uncertainty in the determination of a the coefficient of transition from the relative [1] to absolute intensities. Corresponding error can be estimated at the level of $\sim 10\%$. The r values found for each level listed in Table 1 allow considerable reduction of false placing into the decay scheme of γ-transitions with close energies.

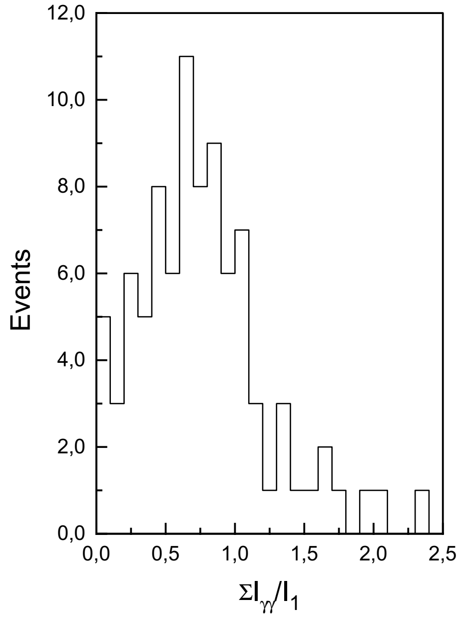

Fig. 1. Frequency distribution of the ratios $r = \sum i_{\gamma\gamma}/i_1$ of the sum cascade intensities to the intensities of their joint primary transitions.

Essential information about the mechanism of reaction of the slow neutron radiative capture can be derived in the future from the comparison of the experimental and model-calculated ratios $i_{\gamma\gamma}/i_2$ (10$^{\text{th}}$ column in Table 1). In turn, such a value determines the ratio between the intensities of the direct primary transition and a number of cascades with several transitions which populate the same state E_i. The necessity of such analysis for the levels with $E_{ex} > 1$ MeV follows from the data shown in Figs. 2 and 3 which demonstrate considerable discrepancy between the results of models of a nucleus and experimental results.

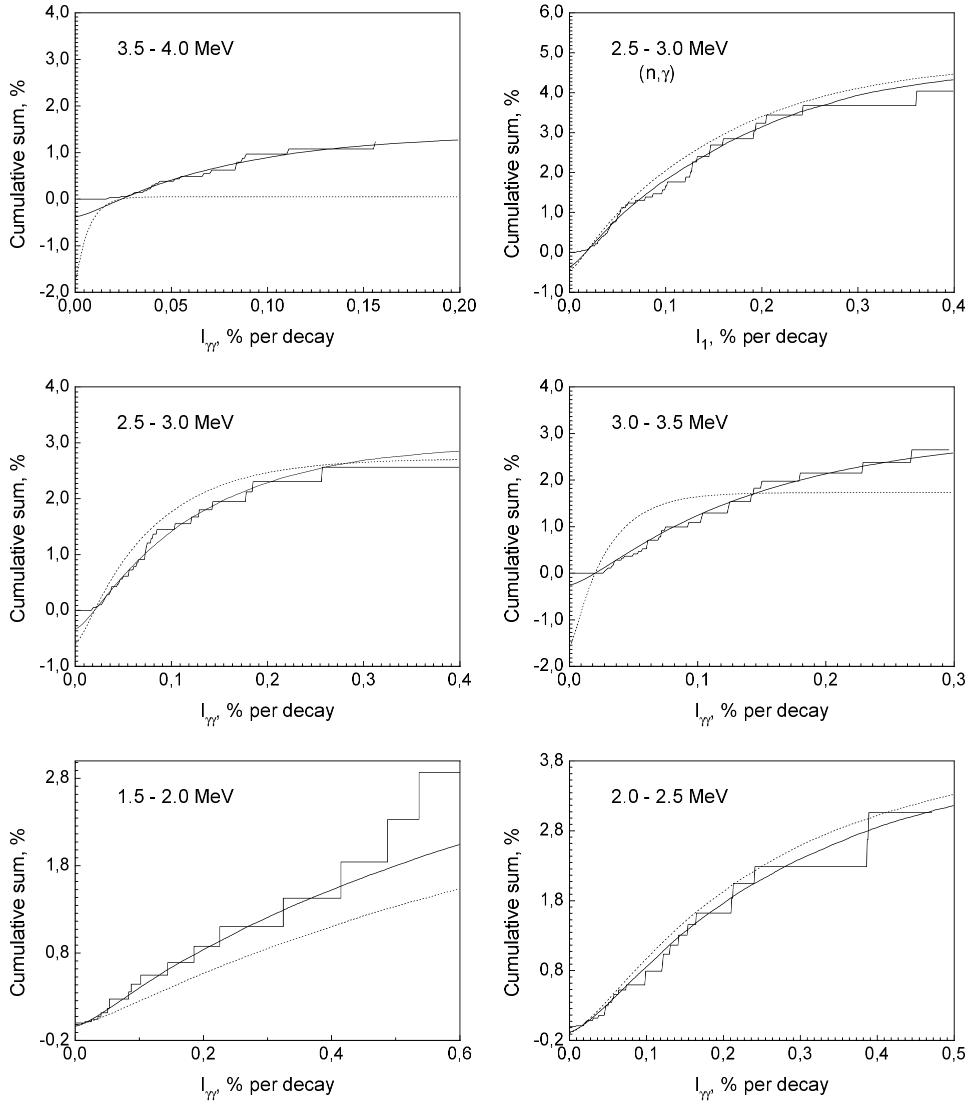

Fig. 2. Number of observed levels of the most intensive cascades in ^{168}Er *(Tables 1 and 2) for excitation-energy intervals of 100* keV *(circles). Curves 1 and 2 represent the predictions of models of Refs. [16] and [25], respectively. Histogram is the estimation of Ref. [15] of level density from the shape of distribution of the cumulative sums of cascade intensities. Triangles with bars represent level density providing simultaneous reproduction in the calculations of both* Γ_λ *and* $I_{\gamma\gamma}$.

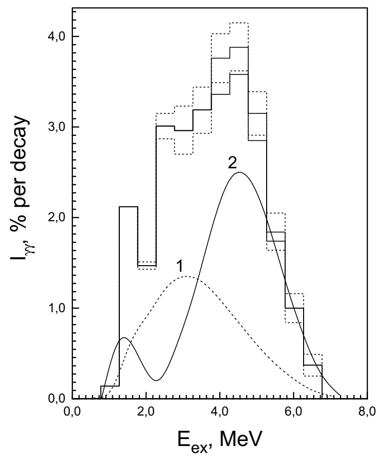

Fig. 3. The interval of probable values of the sum strength functions for $E1$ and $M1$ transitions (multiplied by 10^9) providing correspondence between the experimental and calculated values of Γ_λ and $I_{\gamma\gamma}$. The upper curve represents calculations according to the model of Ref. [20] and under assumption $f(M1) = const$, the lower curve is the same for the model of Ref. [19].

3.2. Verification of the existing decay scheme and new modes of decay

Comparing our data on the decay scheme of ^{168}Er with those from Refs. [1] and [2], one can conclude that the information on both the decay modes on the whole and the sufficiently precise established decay ways of levels above the excitation energy of about 2.5 MeV has been first obtained by us. Our data on the decay scheme of ^{168}Er are listed in Tables 1 and 2. But a matter of larger interest are the cases when, on the grounds of the data on two-step cascades, one can determine the incorrect placement of transitions in the known decay scheme.

Such cases were not found below the excitation energy of 2 MeV, although we did not observe several cascades whose probable secondary transitions were placed in the decay scheme [1,2]. So, we did not observe the three strongest cascades whose 915, 1413, and 1076 keV secondary transitions depopulate, according to [1,2], intermediate levels at 994, 1493, and 1972 keV, respectively. These cascades must have intensity about 10^{-4} per decay. However, this value is close to the registration threshold L_c in our experiment or even less than that.

In the excitation energy interval 2.0 to 2.4 MeV, we did not observe the cascade with a 1407 keV secondary transition ($E_i = 2302.68$ keV) and $i_{\gamma\gamma} = (1-2)\times 10^{-4}$. At the same time, the data on cascades permitted us to introduce 8 more levels into the decay scheme in this energy interval. This allows the following conclusion: the previous decay scheme of ^{168}Er [2] below $E_i \simeq 2.4$ MeV has been established with a very high reliability, at least for the most intense transitions observed in the (n, γ) reaction.

3.3. Estimation of completeness of the system of established levels

The presence of the registration threshold for specific transitions or cascades, together with the problems concerning the reconstruction of the decay scheme on the basis of experimental spectra, motivated us to find a method of estimating the number of missing levels. This problem should be treated by taking into account that all two-step cascade spectra consist of:

(a) a number of well-resolved discrete peaks corresponding to cascades with $i_{\gamma\gamma} > L_c$ (in the spectra, a small number of background peaks appears, in very specific cases, and they can be easily identified);

(b) a continuous, low-amplitude distribution related to the large number of low-intensity ($i_{\gamma\gamma} < L_c$) cascades;

(c) a "noise" line with zero mean value (result of subtraction of the background).

As a result of (a), the existing set of cascades (Table 1 and, most of Table 2) practically does not contain false data and can be considered as a "complete" statistical ensemble of random values which have some distribution for intensities $i_{\gamma\gamma} > L_c$. The L_c value for cascades is determined only by the experimental conditions (i.e., by condition (c)). For the data listed in Tables 1 and 2, $L_c \simeq (1-2) \times 10^{-4}$ per decay of the compound state.

There is no reliable information on the shape of the intensity distribution of primary transitions and, all the more so, of the cascades which excite intermediate levels of even-even deformed nuclei in the interval, for example, $2.0 < E_i < 3.5$ MeV. The matrix element of primary transitions at the γ-decay of neutron resonance is the sum of a large number of random items (in the frame of the existing theoretical notions [8] of the structure of nuclear levels and the probabilities of transitions between them). Accounting for this, one can expect that, in the first approach, the divergences of cascade primary transitions with respect to the mean value are described by the Porter-Thomas distribution [14]. As mentioned above, the sum $\sum i_{\gamma\gamma}$ of the cascade intensities measured in the experiment is rather close to that of their primary transitions, i.e., the distribution of this sum is like the random distribution of i_1 [15].

On this basis, we compared the Porter-Thomas distributions (with the parameters providing the best agreement with the experiment) and the sum intensities of cascades (which excite the same intermediate level) in order to estimate the number of missing levels in ^{168}Er. Cumulative sums of the experimental (histograms) and simulated within the Porter-Thomas distribution (curves) cascade intensities for the 0.5 MeV intervals in the excitation energy diapason 1.5 to 4 MeV are shown in Fig. 4.

The results of this comparison are given in Table 3, as well as the results of an analogous analysis performed for primary transitions from Ref. [2]. When considering these results, one should take into account that the process under study is affected by the structure of the matrix element of the primary transition — the presence of one or more items which considerably exceed other components must decrease (in comparison with predictions of [14]) the number of low-intensity cascades (transitions) and increase the number of intensive cascades.

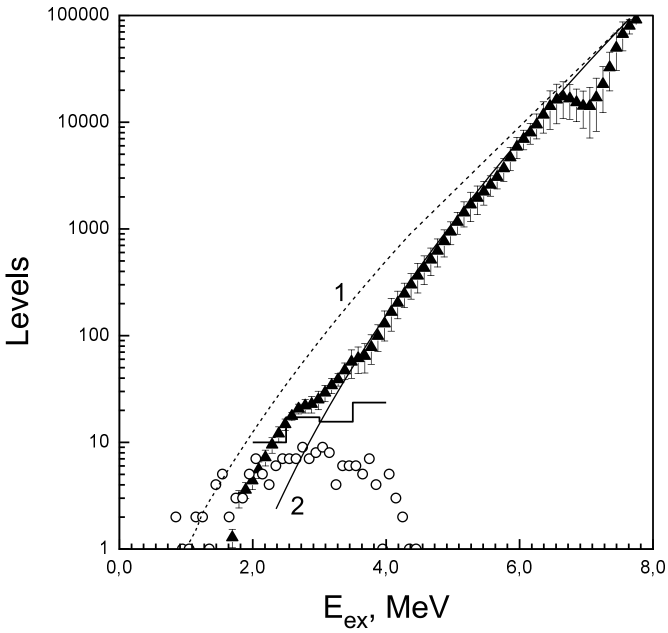

Fig. 4. Cumulative sums of the cascade intensities (primary transitions) for excitation energy intervals of 0.5 MeV *in the interval from 1.5 to 4.0* MeV *versus the running value of the intensity. The histograms represent the experimental data and curves visualize simulations within the Porter-Thomas distributions: solid curve corresponds to a distribution with the parameters providing the best description of the experiment, dashed curve represents the distribution for the same total cascade intensity, but for the level density predicted by the BSFG model [16].*

It should be noted that there are no experimental methods to test validity of the Porter-Thomas law [14] for low-intensity transitions. Taking into account the results of theoretical analysis [8] of the wave function structure of compound-state matrix elements of γ-transitions after its decay, one can assume that this law overestimates the probability of low-intensity cascades. So, the obtained δI and δN values should be considered only as upper estimates. Nevertheless, one should expect the presence of atmost 10 to 15 unknown levels in the 1.5 to 2.5 MeV excitation interval of ^{168}Er.

At higher excitation energies, the situation is radically different. On one hand, a rather good description of cumulative sums of the experimental cascade intensities for $i_{\gamma\gamma} > L_c$ by the Porter-Thomas distribution (corresponding numbers of degrees of freedom N_i^{mod} are listed in Table 3) allows us to hope for correct extrapolation to the $i_{\gamma\gamma} < L_c$ region. On the other hand, the data of Table 3 unambiguously require that we abandon the conventional notion of an exponential increase in the level density when the excitation energy increases (the exponential law is the basic idea for level density models like such as the back-shifted Fermi-gas model with parameters from Ref. [16]).

TABLE 3. The summed experimental, $\sum i^{exp}$, and modelled, $\sum i^{mod}$, intensities (in % per decay) for two-step cascades or primary transitions. L_c is the detection threshold for the cascade, i_{max} is maximum value of the intensity which limits the interval of comparison, N_i^{mod} is the number of intermediate levels excited by dipole primary transitions (under the assumption of an equality of level densities for both parities), Δ is the ratio of $E1$ and $M1$ transitions which provides the best correspondence between experimental and calculated distributions. Here, δi and δN are the mathematical expectations of unobserved intensities and the number of levels corresponding to the sum of low-intensity ($i < L_c$) parts of two Porter-Thomas distributions with $\nu = N_i^{mod}$ for each, $< \rho \times \Delta E >$ is the number of levels predicted according to Ref. [16], excited by primary $E1$ transitions after decay of the ^{168}Er compound state with $J^\pi = 4^+$, in the excitation energy interval considered here.

Interval	1.5-2.0 MeV		2.0-2.5 MeV		2.5-3.0 MeV		3.0-3.5 MeV	3.5-4.0 MeV
for:	$(n,2\gamma)$	(n,γ)	$(n,2\gamma)$	(n,γ)	$(n,2\gamma)$	(n,γ)	$(n,2\gamma)$	$(n,2\gamma)$
$\sum i^{exp}$, %	3.5	3.3	3.53	3.79	3.11	4.5	2.94	1.39
$\sum i^{mod}$, %	3.65	3.5	4.0	5.0	3.3	5.2	3.3	1.8
L_c, %	0.015	0.012	0.015	0.016	0.02	0.017	0.02	0.024
i_{max}, %	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
N_i^{mod}	12	17	23	42	47	63	38	40
Δ	0.18	0.25	0.4	0.2	0.35	0.21	0.37	0.36
δi, %	0.04	0.04	0.1	0.2	0.3	0.4	0.3	0.4
δN,	7	7	14	36	51	64	39	53
$\langle\rho\times\Delta E\rangle$	8	8	26	26	76	76	203	459

There are apparently only two solutions of this problem. The first: we have no grounds to exclude the potential possibility of the coexistence of two or more systems of nuclear levels (with $J = 2 - 5$ in the case of the nucleus under study) above a nuclear excitation energy of 2.0-2.5 MeV. These systems can include different numbers of states and their excitation probabilities can differ, at least, by a factor of 100 or more. (When modelling the distributions shown in Fig. 4, we accounted for the fact that cascades with $E1$ and $M1$ primary transitions have different but comparable intensities (the Δ value in Table 3)). A potential discrepancy in excitation probabilities can appear only for the cascades with $i_{\gamma\gamma} < L_c$. This statement is motivated by an analysis of the data listed in Table 3 and plotted in Fig. 2. The joint interpretation of these data is possible only in the framework of the assumption that the number of the cascade intermediate levels appearing in the energy interval from 2 to 4 MeV of ^{168}Er is almost constant, and the discrepancy between the experiment and exponential extrapolation of the level density cannot be explained by the traditional "omission" of weakly excited states.

The alternative to this conventional notion is a different type of the dependence on energy for the density of states excited after thermal neutron capture in the ^{167}Er target-nucleus. The method providing realistic estimation of level density from the measurements of the $(n, 2\gamma)$ reaction was first described in Ref. [17].

Further development of this method allowed an estimation of both the level density and sums of the strength functions

$$f = <\Gamma_{\lambda i}> /(E_\gamma^3 \times A^{2/3} \times D_\lambda) \qquad (2)$$

(partial widths) of $E1$ and $M1$ transitions by modelling complete sets of their most probable values within the framework of numerical solution of equations which determine:

(a) experimental value of the total radiative width of the ^{168}Er compound state: $\Gamma_\lambda = \sum_i \Gamma_{\lambda i} \times (\rho \Delta E) = 88(2)$ meV [18];

(b) dependence of the cascade intensity on the excitation energy of their intermediate levels (Fig. 5).

Modelling is performed with the condition of positivity of all parameters under consideration.

As can be seen from Fig. 2, the exponential extrapolation [16] does not allow one to calculate the parameters of the cascades γ-decay to a precision achieved in the experiment. For example, it overestimates level density at $E_{ex} \sim 0.5B_n$ by an order of magnitude. At the same time, the estimated (Fig. 3) sums of radiative strength functions of $E1$ and $M1$ transitions also differ from the predictions of the sufficiently simple models [19-21], which are usually used for calculation of such parameters as, e.g., the total radiative width.

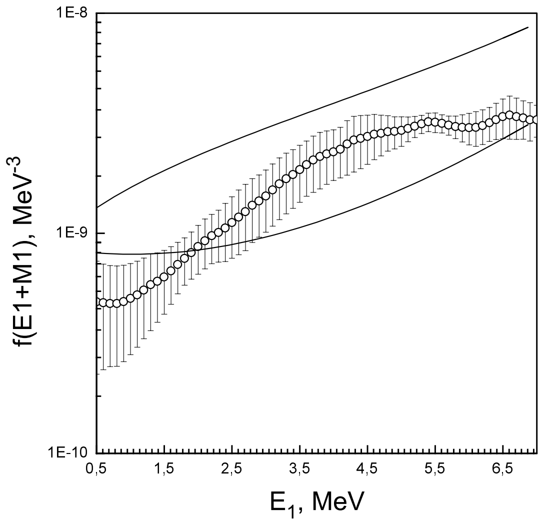

Fig. 5. Total two-step cascade intensities (in % per decay) as a function of the excitation energy. The histograms represent the experimental intensities (summed in energy bins of 500 keV*) with ordinary statistical errors; the maximum possible estimates of probable systematic errors (the δi values from Table 3) are shown by black rectangles. Curves 1 and 2 correspond to calculations within the models of Refs. [16] and [25], respectively.*

3.4. On the structure of the cascade intermediate levels

We confirmed the existence or derived for the first time decay modes for 17 of 40 known levels in the interval 1.5-2.0 MeV, for 26 levels in the interval 2.0-2.5 and for 34 levels in the interval 2.5-3.0 MeV. Decay modes of the states with $E_{ex} > 2.5$ MeV are derived, in practice, for the first time. As a rule, intensity of the primary transitions amounts to 0.02-0.5% per decay. The lack of data on the secondary transitions with $E_2 > 2525$ keV in Ref. [2] makes it difficult to theoretically investigate possible structure of the levels with $E_{ex} > 2.5$ MeV (there can be, for example, data on multipolarity of transitions or on spectroscopic factors from the (d, p) or (d, t) reactions). From the practical point of view, considerable statistical errors in determination of cascade intensities as well as theoretical problems with description of the structure of the levels with $E_{ex} > 2.5$ MeV make it difficult to apply the theoretical method of Ref. [6] to these states, too.

The existing nuclear models [6,7] cannot describe the structure of any level above the $2-3$ MeV excitation energy and, moreover, does not allow the calculation energies to a precision which is suitable for a comparison with experiment. The information which can be provided by theory for the interpretation of experimental results at this excitation has a very general character. For example, there are levels with a number of quasiparticles, states of mixed type, whose structure is determined by both quasiparticle and phonon excitations. Even in this case, the theory provides a possibility of, although qualitative and sometimes contradictory, interpretation of experiment. This allows one to extract some information on the properties of nuclear matter. The objects of our interest are the results of the investigation of regularity of fragmentation of different states performed by Malov and Soloviev [22]. They showed that the degree of fragmentation quickly decreases as the number of quasiparticles and phonons in the wave function of some state increases. In particular, such components of the wave function as, e.g., four quasiparticles$\otimes$phonon or two phonons (quadrupole, octupole...) can be fragmented only over some neighbouring levels. This theoretical result, in conjunction with the known fact of initial harmonicity of the spectra of vibrational excitations, provides the only possibility to interpret the results given in Sect. 4.2.

As a result, new experimental data require the development of new model ideas. Moreover, this is necessary as the existing theoretical calculations for few-quasiparticle and collective states with low spins are mainly limited by the excitation energies of $2-3$ MeV.

4. Analysis

4.1. Total intensities of two-step cascades at different excitation energies

From the coincidence data stored in the experiment, it is very simple to construct a total intensity distribution of the two-step cascades which includes both the primary and secondary transitions. Quanta ordering for a majority of the intensive cascades, whose parameters are given in Tables 1 and 2, was determined [13] under obvious condition that the primary transitions in different cascades proceeding via the same intermediate level have the same energy in different spectra; secondary transitions of these cascades have different energies. As follows from Table 3, the main part of the intensity corresponding to the excitation of levels below $\sim$ 3.5 MeV was established in the experiment. By subtracting this part of intensity from the experimental distributions, we get the intensity of the cascades which populate higher-lying levels. Thus, as was first suggested in Refs. [23] and [24], one can determine the dependence of the cascade intensities on the energy of their intermediate levels for practically the total excitation interval $E_{ex} \simeq B_n$.

Such a dependence for ^{168}Er, obtained after summation of the cascade intensities over all final levels and in the intermediate level energy intervals $\Delta E = 0.5$ MeV, is shown in Fig. 5. Experimental data (histograms) are compared with two variants of the calculations. The shape of the dependence of the level density on the nuclear excitation energy in the first variant was determined within model of Ref. [16], and in the second variant, within the model of Ref. [25]. Both variants used conventional models [20,21] to describe the radiative widths. As can be seen from this figure, the calculation based on the Fermi-gas level density model [16] (curve 1) cannot correctly predict the intensity of cascades at high excitations of ^{168}Er. This situation is typical for any deformed nucleus from the region of the 4s-resonance of the neutron strength function. A possible explanation of this effect directly follows from an analysis of basis of the models of Refs. [16] and [25].

4.2. Factors determining level density at low excitations

Figure 2 shows the number of cascade intermediate levels in the 100 keV energy interval as a function of the excitation energy. Experimental data (points) are compared with the predictions of the conventional back-shifted Fermi-gas model [16] and model of Ref. [25]. As can be seen from this figure, the model [25] reproduces the experimental data above 4 MeV but does not below 4 MeV. This model accounts for co-existence and interaction of vibrational and quasiparticle excitations within the adiabatic approach. But it probably does not correspond to reality below 4 MeV. A possible explanation of this situation can be obtained from an analysis of the spacings between the intermediate levels (or their multiplets) of the most intense cascades. The algorithm of this analysis is described in Ref. [26] and some of its results concerning ^{168}Er are given below.

Figure 6 demonstrates the absolute intensity of all two-step cascades placed in the decay scheme smoothed by the Gaussian function with the parameter $\sigma = 25$ keV (see Tables 1 and 2). These are shown separately for cascades terminating at the levels of the γ-band and the band of the ground state. As seen from the figure, the spacings between the most intensive peaks in this distributions are almost equal. These peaks can be placed in almost equidistant "bands", the search for which was performed by means of the autocorrelation function

$$A(T) = \sum_E F(E) \times F(E+T) \times F(E+2T). \tag{3}$$

The values of the autocorrelation function versus the equidistant period T are shown

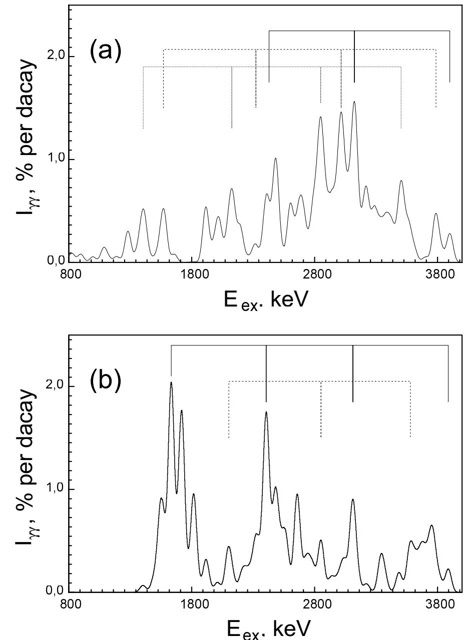

Fig. 6. The dependence of the intensities (% per decay) of the resolved cascades listed in Tables 1 and 2 on the excitation energy. Possible "bands" of almost harmonic excitations of the nucleus are marked. The "smoothing" parameter $\sigma = 25$ keV *was used. (a) — for cascades to levels of the band of the ground state, (b) — to levels of the γ-band.*

in Fig. 7. From this figure, it follows that, indeed, one or more groups, consisting of at least 3 intermediate levels (or their close doublets) for the strongest cascades terminating at levels of the γ-band, appear in ^{168}Er. These groups are marked in Fig. 6. It should be noted that the problem considered here cannot have a unique solution, even in principle [27], if only the ensemble of cascades following thermal neutron capture in a single nucleus is involved in the analysis. An unambiguous proof for the presence of the observed regularity can be obtained only after studying the two-step cascades in a number of resonances of the ^{167}Er target-nucleus.

Nevertheless, using the data on the equidistant periods [26] for nuclei studied by us earlier, one can choose the value $T = 740$ keV as the most probable equidistant period for ^{168}Er. The dependence of the probable equidistant periods on the number N_b of the boson pairs in the unfilled nuclear shells for the group of N-even nuclei in which two-step cascades were studied is shown in Fig. 8.

At present, a direct determination of structure of the levels entering into the observed equidistant "bands", observation of vibrational components in wave functions and identification of type of vibration is impossible. But the redistribution of the excitation energy between quasiparticles and phonons is the simplest and, probably, sole explanation [26] of non-exponential behaviour of level density below ~ 4 MeV.

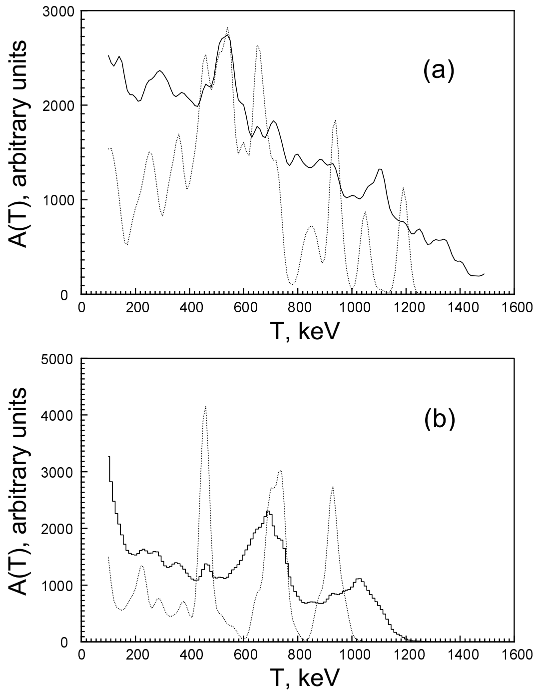

Fig. 7. The values of the functional $A(T)$ for the two registration thresholds of the most intensive cascades: the solid curve corresponds to all resolved cascades listed in the tables; the dashed curve corresponds to cascades with intensities higher than 0.1% per decay. Notations are the same as in Fig. 6.

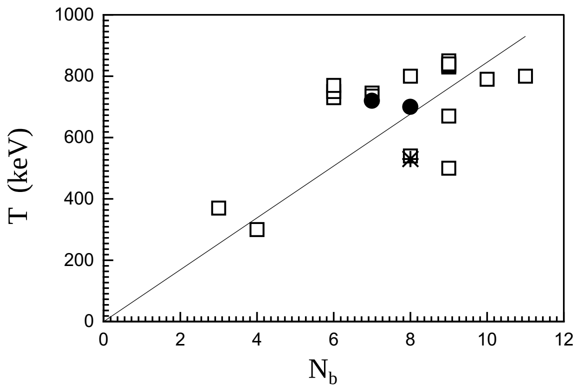

Fig. 8. The values of the equidistant period, T, for ^{177}Lu *(asterisk) and for even-even nuclei studied earlier (rectangles) as a function of the number of boson pairs, N_b, in the unfilled shells. The $\otimes$ show the ϵ_d values for the* ^{110,112}Cd *nuclei. Line extrapolates the possible linear dependence.*

5. Conclusions

The analysis of the experimental data on the two-step cascades proceeding between the compound state and a group of low-lying levels of ^{168}Er shows that the γ-decay process of this nucleus reveals the same main peculiarities as those observed earlier for other deformed nuclei. These results support previous assumptions about the factors affecting the γ-decay:

(a) the sharp change in nuclear properties at the excitation energy of 3 – 4 MeV;

(b) below this excitation energy one should expect the domination of levels whose wave functions include, possibly, vibrational-type excitations. Such preliminary conclusion can be made by the virtue of a strengthening of the widths of the cascade transitions to the low-lying levels of the nucleus under study. The greatest strengthening can be related to the practically harmonic nuclear vibrations having a phonon energy of 700 – 750 keV, as well as a considerable decrease of the number of excited states in the energy interval from 2 to 4 MeV.

Similar results follow also from the modern precise analysis of the interaction cross-sections of neutrons with actinides [28].

Acknowledgements

Authors' thanks are due to Ms. Ann Schaeffer for her help in preparation of the English version of this paper. This work was supported by RFBR Grant No. 95-02-03848.

References

[1] W. F. Davidson et al., J. Phys. G., Nucl. Phys. **17** (1991) 1683.

[2] V. S. Shirley, Nucl. Data Sheets **71** (1994) 455.

[3] A. Jungclaus, Phys. Rev. C. **49** (1994) 88.

[4] R. L. Gill et al., Phys. Rev. C **54** (1996) 2276.

[5] S. A. Berendakov at al., Yad. Phys. **61** (3) (1998) 232.

[6] V. G. Soloviev et al., J. Phys. G., Nucl. Phys. **20** (1994) 113; V. G. Soloviev et al., Part. Nucl. **27(6)** (1997) 1643.

[7] V. G. Soloviev, *Theory of Atomic Nuclei: Quasiparticles and Phonons*, IoP Publ., Bristol and Philadelphia (1992); V. G. Soloviev, *Theory of Complex Nuclei*, Pergamon Press, Oxford (1976). V. M. Belenkii and E. P. Grigoriev, *Structure of Even Nuclei*, Moscow (1987) (in Russian).

[8] V. G. Soloviev, Part. Nucl. **3** (4) (1972) 770.

[9] S. T. Boneva et al., Izv. AN SSSR, Ser. Fiz. **55** (5) (1991) 841.

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

[11] S. T. Boneva et al., Sov. J. Part. Nucl. **22** (6) (1991) 698.

[12] A. M. Sukhovoj and V. A. Khitrov, Sov. J.: Prib. Tekhn. Eksp. **5** (1984) 27.

[13] Yu. P. Popov, A. M. Sukhovoj, V. A. Khitrov and Yu. S. Yazvitsky, Izv. AN SSSR, Ser. Fiz. **48** (1984) 1830.

[14] C. F. Porter and R. G. Thomas, Phys. Rev. **104** (2) (1956) 483.

[15] A. M. Sukhovoj and V.A.Khitrov, Phys. At. Nuclei **62** (1) (1999) 19.

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

[17] V. A. Khitrov, A. M. Sukhovoj, *Proc. VI Int. Seminar on Interactions of Neutrons with Nuclei, Dubna (1998)*, E2-98-202, Dubna (1998) 172.

[18] S. F. Mughabghab, *Neutron Cross Sections*, Vol. 1. Part B, Academic Press, New Yorl (1984).

[19] S. G. Kadmenskij, V. P. Markushev and W. I. Furman, Sov. J. Nucl. Phys. **37** (1983) 165.

[20] P. Axel, Phys. Rev. **126** (2) (1962) 671.

[21] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics*, McGraw-Hill, New York (1952).

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

[23] S. T. Boneva, V. A. Khitrov, A. M. Sukhovoj and A. V. Vojnov, Z. Phys. A **338** (1991) 319.

[24] S. T. Boneva, V. A. Khitrov, A. M. Sukhovoj and A. V. Vojnov, Nucl. Phys. A **589** (1995) 293.

[25] A. V. Ignatyuk, *Proc. IAEA Consultants Meeting on the Use of Nuclear Theory in Neutron Nuclear Data Evaluation, Trieste, Italy, 8 Dec. 1975*, IAEA-190 (1976) Vol. 1, p.211.

[26] V. A. Khitrov and A. M. Sukhovoj, Izv. RAN., ser. fiz., **61(11)** (1997) 2068.

[27] E. V. Vasilieva et al., Bull. Russian Acad. Science, Physics **57** (1993) 1582.

[28] *Handbook for Calculation of Nuclear Reaction Data*, IAEA-TECDOC-1034, Vienna (1998).

ISTRAŽIVANJE γ-RASPADA SLOŽENE JEZGRE ^{168}Er NASTALE REAKCIJOM $(n, 2\gamma)$

Analiziramo podatke o spektrima dvojnih gama kaskada izmedu stanja složene jezgre i nisko-ležećih stanja (E_f < 1.1 MeV) ^{168}Er. Podaci o najintenzivnijim eksperimentalno-razlučenim kaskadama se rabe za provjeru i utočnjenje već poznate sheme raspada te jezgre i njeno proširenje na više energije uzbude. Stupanj potpunosti se odredjuje numerički za shemu sa 91 stanjem za E_{ex} < 3.14 MeV. Ukupni intenziteti svih kaskada (uključiv i one koje nisu eksperimentalno razlučene a čine neprekidne dijelove spektra) primjenjuju se za ispitivanje modela koji neuspješno pokušavaju objasniti i opisati kaskadne procese γ-raspada u području energija uzbude do energije vezanja neutrona B_n.