Experimental Gamma Cascade Intensity Distributions from the ^{171}Yb(n,γ) Reaction

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Abstract

In the present paper, the gamma cascade intensity distributions of ^{172}Yb from the ^{171}Yb(n,γ) reaction are determined. The obtained gamma cascade intensity distributions can be used to simultaneously extract the nuclear level density and radiative strength function of ^{172}Yb excited nucleus by means of the Dubna method. The latter has been applied to 43 nuclei, whose atomic number ranges from 28 to 200, but ^{172}Yb. Thanks to the high quality gamma-gamma coincidence spectrometer and the high statistics achievement, the gamma cascade intensity distributions obtained for ^{172}Yb within the present work is the most accurate in comparison to all the 43 investigated nuclei.

Introduction

We have already known that the nuclear level density and radiative strength function are all together important quantities, which describe the average properties of excited nuclei in the high-excitation-energy region [1]. As ^{172}Yb is an even-even, deformed, and heavy nucleus, its nuclear properties are useful information for confirming as well as improving the nuclear models of high-mass nuclei near the stability line.

In the excited energy below the neutron binding energy, the Dubna method [2] is widely used to simultaneously extract the nuclear level density and radiative strength function from the measured gamma cascade intensity distributions. Although this method has been applied to 43 nuclei whose atomic number ranges between 28 and 200 [3], the ^{172}Yb nucleus has not been studied yet.

Within the Dubna method, the gamma cascade intensity distributions are determined from the two-step-cascade (TSC) spectra, corresponding to the gamma cascades from the compound state to the different final excited states. The events, which are due to the Compton scattering, are significantly suppressed, particularly in the TSC spectra corresponding to low-energy final states. Therefore, the obtained gamma cascade intensities are highly reliable.

In the present paper, we present the experimental gamma cascade intensity distributions of the excited ^{172}Yb nucleus measured via the thermal neutron capture reaction. A nuclear level scheme, which is constructed from the resolved cascade decays using the maximum likelihood method, is also given.

Experimental

The gamma-gamma coincidence experiment was carried out on the neutron beam No.3 of Dalat Nuclear Research Reactor. The latter provided a neutron beam whose flux and diameter were 1.7×10^5 n/cm^2/sand 2.5 cm, respectively. The target was 0.56 g Yb_2O_3 powder sealed in a plastic bag. The enrichment of ^{171}Yb in this target is more than 95.5%, that is, the ^{171}Yb mass is about 0.48 g. The percentages of the other impurities in the target is small enough to not cause net influences on the obtained spectroscopic data of ^{172}Yb nucleus. The cascade decay data were recorded for about 830 hours using two HPGe detectors whose relative efficiency equal to 35% of the standard NaI(Tl) scintillator detector (3 in×3 in× 3 in). The measurement was performed using the "close" geometry as given in Fig. 1, in which the distance from the target to the detector windows are only 5 cm. The energy threshold of the spectrometer was set to 520 keV.

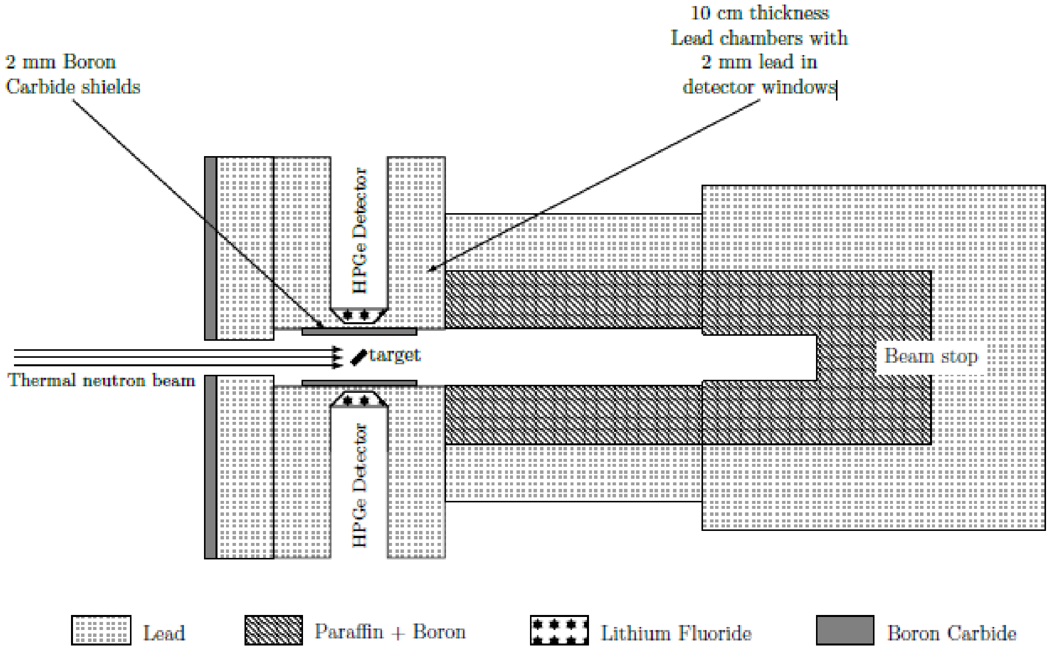

Fig. 1. The "close" geometry used for measuring the gamma – gamma coincidences.

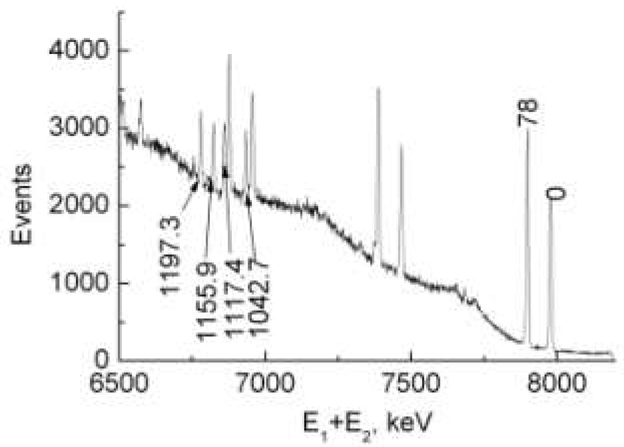

Fig. 2. The most informative part of the spectrum of sums of coincident pulse's amplitudes for ^{171}Yb(n_{th},2γ) reaction. The energies of the final levels of cascades (in keV) are pointed near peaks of the full energy capture.

The most informative part of the spectrum of sums of coincident pulse's amplitudes for ^{172}Yb is shown in Fig. 2. It can be easily seen from this figure that there is almost no Compton background under the summation peaks corresponding to the ground state and the final state E_f = 78.8 keV. However, the Compton background is rather high under the other summation peaks corresponding to the other four final states. A number of peaks caused by single- and double-escape events can also be clearly seen.

Fig. 3. TSC spectra corresponding to the cascade decays from the compound state to the ground state (left panel) and the final state $E_f = 78.8$ keV (right panel) of ^{172}Yb.

Fig. 3 shows the TSC spectra corresponding to the cascades decays from the compound state to the ground state and the first excited state $E_f = 78.8$ keV of ^{172}Yb. Within these TSC spectra, more than 66% of the collected events are belongs to the resolved cascade decays; consequently, the contribution of the unresolved cascade decays in the obtained gamma cascade intensity distributions are not larger than 33%. It is noted that the energy resolution and the symmetry of the TSC spectra are improved since the algorithm for digitally improving the energy resolution [4] were applied.

In order to determine the absolute intensity of the primary transitions within the investigated reaction, the gamma-rays intensities of 5538 keV transition were measured via the prompt gamma spectrum of a complex $^{27}Al+^{171}Yb$ target. The intensity of 5538 keV transition obtained within the present work is in agreement with that in Ref. [5] within the experimental uncertainty.

Data Analysis

Resolved cascade decays

A pair of gamma transition corresponding to the cascade decay from the compound state to a certain final state is represented as a pair of peak in the corresponding TSC spectrum. These two peaks are symmetrical via the center of the TSC spectrum, and their peak area is proportional to the cascade transition intensity. By determining the position and area of all the peaks in all the obtained TSC spectra, one can achieve a list of cascade transitions together with their relative intensities. These relative intensities are then converted to the absolute intensities using the intensity of a well-known primary transition, such as 5538 keV transition in the case of ^{172}Yb experiment.

Construction of the gamma cascade scheme

It is obvious that the gamma – gamma coincidence spectrometer does not provide information to identify the primary and secondary transitions of a certain cascade decay, therefore a method is needed to construct the gamma cascade scheme from the obtained list of cascade transitions. The maximum likelihood method [2] was known as an efficient one. Consequently, within the present work, the gamma cascade scheme is built by means of themaximum likelihood method.

Since the result obtained by using the maximum likelihood can be false in case of cascade transitions which appear in only one TSC spectrum, the data in Ref. [5] and the ENSDF library are also used as additional information to construct the gamma cascade scheme.

Unresolved cascade decays

A TSC spectrum consists of three components [6]:

1. a set of discrete peaks corresponding to the resolved transitions;
2. A number of low intensity transitions, also known as unresolved cascade decays;
3. And a noise line, which has zero average value.

As the resolved part of a TSC spectrum, which is caused by the resolved transitions, can be easily recreated using the list of resolved cascade decays, one can obtain the unresolved part of the TSC by subtracting the resolved part from the TSC spectrum. After that, the unresolved part of the TSC spectrum is averagely smoothed to remove the noise.

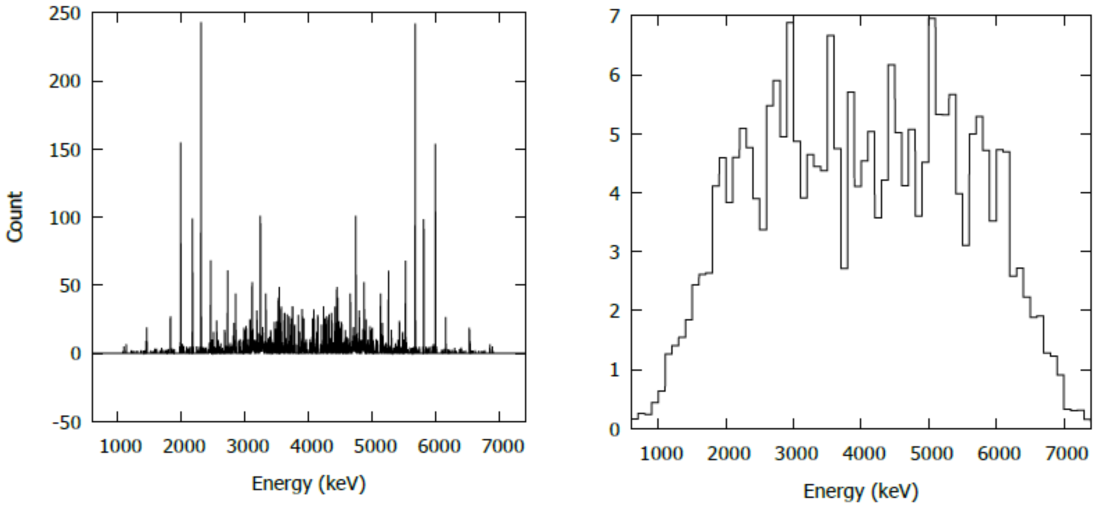

Fig. 4. The resolved part (left panel) and the unresolved part (right panel) of the TSC spectrum corresponding to cascade decay from the compound state to the ground state of ^{172}Yb (Fig.3, left panel). The unresolved part is averaged over 100 channels to remove the noise line.

Gamma cascade intensity distributions $I_{\gamma\gamma}(E_1)$

Since both primary and secondary transitions are accumulated in the TSC spectrum, the TSC spectrum is the sum of the primary gamma intensity distributions $I_{\gamma\gamma}(E_1)$ and secondary gamma intensity distributions $I_{\gamma\gamma}(E_2)$. Within the Dubna method, it is necessary to determine the $I_{\gamma\gamma}(E_1)$ as accurately as possible.

The resolved part of the $I_{\gamma\gamma}(E_1)$ can be easily determined as the maximum likelihood method allows us to determine a reliable nuclear level scheme based on the experimental list of discrete cascade transitions. However, the determination of the unresolved part of $I_{\gamma\gamma}(E_1)$ is complex because for this part, there is no information to separate the primary and secondary transitions. Because of the latter, in order to determine the unresolved part of $I_{\gamma\gamma}(E_1)$ we assume that the unresolved parts of $I_{\gamma\gamma}(E_1)$ and $I_{\gamma\gamma}(E_2)$ are identical in the unresolved part of the TSC spectrum (Fig. 4, right panel) [6]. Since this assumption can cause some distortions in the medium energy of the $I_{\gamma\gamma}(E_1)$ distributions, one should reduce the distortions by increasing the contribution of the resolved part. Besides, effects of the distortions on the nuclear level scheme and radiative strength function obtained using the Dubna method is insignificant in many cases [6].

Results and Discussion

Gamma cascade scheme

Table 1 present the list of obtained gamma cascades together with their intensity. These cascades decay from the compound state to the ground state and five low-lying states whose energies are 78.8, 1042.7, 1117.4, 1155.9 and 1197.3 keV. The uncertainty of the gamma cascade intensity is almost less than 30%. From this table, we can see that most of the resolved cascade are belongs to the decay to the ground state and the first excited state E_f = 78.8 keV. It is obvious that the spectroscopic data corresponding to these two final states are in high quality because of the very low Compton background under the corresponding summation peaks together with their large statistics. For the other final states, the spectroscopic data are worse due to the high Compton background. Additionally, the statistical count of the summation peaks corresponding to these final states are much less than those of the ground state and 78.8 kev state. For these reasons, only 79 cascades presented in the Table 1 belongs to the TSC spectra of 1042.7, 1117.4, 1155.9 and 1197.3 keV states.

Table 1. The gamma cascade scheme of ^{172}Yb. E_i is energy of intermediate states. $i_{\gamma\gamma}$ is absolute intensity of the cascade, normalized to 10^6 decays.

E_1+E_2=8020 keV								
E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$	E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$	E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$
6902.6	1117.4	90±16	6864.6	1155.4	123± 25	6553.8	1466.2	180± 33
6542.9	1477.1	361± 41	6419.5	1600.5	66± 16	6410.9	1609.1	66±25
6312.1	1707.9	74±25	6240.9	1779.1	49±16	6170.5	1849.5	549± 66
6025.0	1995.0	107±33	6010.0	2010.0	3214± 139	5982.1	2037.9	139±33
5966.2	2053.8	107±33	5961.3	2058.7	107±33	5917.0	2103.0	98±33
5859.5	2160.5	98±33	5825.4	2194.6	2099±123	5708.4	2311.6	98±33
5691.7	2328.3	5158±197	5666.5	2353.5	98±33	5645.1	2374.9	90±33
5556.0	2464.0	180±33	5539.7	2480.3	1451±90	5531.7	2488.3	123±33
5516.2	2503.8	213±41	5495.1	2524.9	344±49	5481.9	2538.1	107±33
5445.1	2574.9	525±57	5437.8	2582.2	123±33	5421.6	2598.4	213±41
5398.7	2621.3	115±33	5381.4	2638.6	156±41	5353.6	2666.4	82
5272.7	2747.3	1328±107	5240.7	2776.3	131±41	5233.6	2786.4	164±41
5208.0	2812.0	115±41	5191.2	2828.8	156±41	5185.1	2834.9	279±57
5175.2	2845.4	484±74	5147.2	2872.8	976±90	5147.2	2872.8	139±41
5035.8	2984.2	205±49	4986.3	3033.7	230±49	4982.0	3038.0	443±57
4960.9	3059.1	139±33	4952.3	3067.7	221±41	4899.0	3121.0	377±49
4889.9	3130.1	1148±82	4881.9	3138.1	230±41	4867.0	3153.0	115±33
4860.1	3159.9	213±41	4854.3	3165.7	205±41	4835.3	3184.7	197±49
4814.5	3205.5	713±90	4805.6	3214.4	336±20	4798.6	3221.4	164±49
4789.5	3230.5	180±49	4765.2	3254.8	279±66	4758.9	3261.1	2255±164
4739.3	3280.7	287±66	4723.6	3296.4	435±82	4718.5	3301.5	328±74
4711.4	3308.6	205±57	4673.3	3346.7	968±90	4664.2	3355.8	172±41
4637.3	3382.7	238±49	4614.0	3406.0	254±66	4596.3	3423.7	377±57
4560.6	3459.4	180±41	4537.4	3482.6	533±66	4523.5	3496.5	385±90
4499.5	3520.9	533±74	4476.0	3544.0	910±90	4462.0	3558.0	1107±98

E_1+E_2=8020 keV										
E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$
4449.5	3570.5	517±74		4427.3	3592.7	344±74		4421.6	3598.4	115±41
4414.8	3605.9	180±41		4385.0	3635.0	541±74		4360.4	3659.6	238±49
4351.1	3668.9	262±49		4344.8	3675.2	246±49		4338.2	3682.2	640±80
4321.1	3698.9	156±41		4304.8	3715.2	615±90		4299.2	3720.8	279±57
4278.5	3741.5	492±82		4272.3	3747.7	582±82		4263.6	3756.4	197±49
4252.2	3767.8	771±90		4220.2	3799.8	484±74		4210.9	3809.1	148±49
4172.7	3847.3	148±49		4154.5	3865.5	123±49		4144.0	3876.0	353±57
4124.5	3895.5	107±33		4111.9	3908.1	246±49		4102.5	3917.5	730±74
4093.6	3926.4	213±41		4063.1	3956.9	180±41		4057.4	3962.6	131±41
4046.7	3973.3	107±33		4040.9	3979.1	230±49		4036.0	3984.0	172±49
3941.3	4078.7	574±66		3857.2	4162.8	640±90		3788.7	4231.3	131±49
3641.3	4378.7	656±82		3588.2	4431.8	771±98		3491.8	4528.2	230±74
3440.2	4579.8	189±41		3429.6	4590.4	238±49		3409.8	4610.2	254±66
3388.3	4631.7	131±41		3337.9	4682.1	205±41		3289.3	4730.7	172±49
3245.4	4774.6	328±57		3191.4	4828.6	82±33		3177.9	4842.1	221±57
3146.8	4873.2	394±49		3098.0	4922.0	566±57		3071.9	4948.1	123±33
3022.8	4997.2	369±49		3004.0	5016.0	410±66		2997.1	5022.9	123±41
2942.2	5077.8	221±57		2919.1	5100.9	205±41		2866.9	5153.1	213±49
2839.8	5180.2	115±49		2818.2	5201.8	115±41				

E_1+E_2=7942 keV										
E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$
6977.2	1042.8	1635±73		6902.6	1117.4	317±37		6864.6	1155.4	720±61
6821.5	1198.5	976±61		6656.9	1363.1	49±12		6615.5	1404.5	659± 61
6553.8	1466.2	451±49		6542.9	1477.1	988±73		6226.1	1793.9	1464±98
6170.5	1849.5	817±73		6125.7	1894.3	1671±98		6111.9	1908.1	85±24
6062.0	1958.0	183±49		6010.0	2010.0	1696±122		5973.0	2047.0	171±49
5946.6	2073.4	159±49		5917.0	2103.0	573±73		5825.4	2194.6	854±98
5792.5	2227.5	403±73		5743.5	2276.5	20724		5708.4	2311.6	476±73
5691.7	2328.3	2098±159		5678.2	2341.8	659±85		5645.1	2374.9	1196±134
5633.8	2386.2	195±61		5556.0	2464.0	268±61		5539.7	2480.3	22216± 537
5516.2	2503.8	366±61		5460.1	2559.9	207±49		5445.1	2574.9	232±49
5415.5	2604.5	183±49		5392.3	2627.7	195±49		5365.1	2654.9	146±49
5353.6	2666.4	122±49		5338.6	2681.4	171±49		5272.7	2747.3	146±49
5240.7	2776.3	220±61		5237.8	2782.2	146±61		5233.6	2786.4	171±49
5208.0	2812.0	256±61		5198.6	2821.4	220±49		5185.1	2834.9	390±61
5175.2	2845.4	220±60		5157.4	2862.6	378±73		5147.2	2872.8	2867±171
5140.2	2879.8	146±49		5131.8	2888.2	427±73		5060.0	2960.0	220±49

5035.8	2984.2	329±61		5028.7	2991.3	268±61		5007.2	3012.8	244±61
4989.2	3003.8	195±61		4982.0	3038.0	134±49		4952.3	3067.7	195±61
4926.6	309.4	281±61		4911.6	3108.4	195±61		4899.0	3121.0	1074±110
4889.9	3130.1	525±85		4881.9	3138.1	220±61		4805.6	3214.4	159±31
4779.4	3240.6	171±49		4771.3	3248.7	122±37		4758.9	3261.1	427±73
4739.3	3280.7	329±61		4728.7	3291.3	415±61		4718.5	3301.5	598±73
4685.2	3334.8	256±49		4673.3	3346.7	671±73		4637.3	3382.7	244±61
4623.7	3396.3	159±49		4596.3	3423.7	207±49		4560.6	3459.4	146±49
4527.0	3493.0	305±122		4523.5	3496.5	305±122		4499.5	3520.9	122±40
4493.4	3526.6	232±61		4476.0	3544.0	488±73		4462.0	3558.0	415±73
4442.2	3577.8	476±85		4433.7	3586.3	207±61		4421.6	3598.4	232±61
4414.8	3605.9	171±61		4393.2	3626.8	329±73		4338.2	3682.2	317±90
4321.1	3698.9	30573		4315.1	3704.9	317±73		4304.8	3715.2	378±110
4278.5	3741.5	159±61		4272.3	3747.7	1061±110		4263.6	3756.4	464±73
4252.2	3767.8	378±73		4220.2	3799.8	281±61		4210.9	3809.1	293±61
4195.0	3825.0	220±61		4172.7	3847.3	256±61		4165.8	3854.2	293±73
4144.0	3876.0	805±98		4138.9	3881.1	183±61		4124.5	3895.5	146±49
4111.9	3908.1	439±85		4102.5	3917.5	610±98		4060.4	3959.6	232±61
4036.0	3984.0	415±85		4031.1	3988.9	586±98		4020.1	3999.9	195±61
3975.5	4044.5	171±49		3941.3	4078.7	98±37		3857.2	4162.8	305±73
3788.7	4231.3	110±49		3641.3	4378.7	342±98		3579.1	4440.9	378±73
3491.8	4528.2	659±98		3473.9	4546.1	122±49		3429.6	4590.4	354±61
3409.8	4610.2	305±73		3388.3	4631.7	378±61		3337.9	4682.1	98±49
3289.3	4730.7	366±73		3233.0	4787.0	159±49		3191.4	4828.6	378±61
3177.9	4842.1	500±85		3146.8	4873.2	512±73		3098.0	4922.0	293±73
3071.9	4948.1	134±61		3022.8	4997.2	293±61		3004.0	5016.0	244±61
2997.1	5022.9	512±85		2942.2	5077.8	671±85		2919.1	5100.9	220±61
2866.9	5153.1	488±73		2839.8	5180.2	171±49		2818.2	5201.8	183±49

E_1+E_2=6977 keV										
E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$
6012.3	2007.7	220±41		5825.4	2194.6	142±43		5539.7	2480.3	562±113
5495.1	2524.9	110±41		5392.3	2627.7	376±97		5028.7	2991.3	344±119
4968.0	3052.0	214±90		4577.4	3442.6	767±349		4523.5	3496.5	535±275
4338.2	3682.2	171±67		4220.2	3799.8	259±81		3513.6	4506.4	198±74
3491.8	4528.2	257±83		3245.4	4774.6	166±76		3233.0	4787.0	328±99

E_1+E_2=6902 keV										
E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$
6194.4	1825.6	118±27		6111.9	1908.1	55±19		6010.0	2010.0	92±29
5825.4	2194.6	937±132		5604.0	2416.0	164±71		5539.7	2480.3	850±172
5412.3	2607.7	231±74		5392.3	2627.7	399±97		5175.2	2845.4	130±48
5131.8	2888.2	122±48		4877.0	3143.0	309±84		4523.5	3496.5	386±151

4501.8	3518.2	708±227		4338.2	3682.2	250±82		4252.2	3767.8	132±63

E_1+E_2=6864 keV										
E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$
5825.4	2194.6	905±107		5743.5	2276.5	128±44		5708.4	2311.6	113±40
5691.7	2328.3	71±29		5539.7	2480.3	605±134		5028.7	2991.3	273±92
4758.9	3261.1	225±80		4637.3	3382.7	441±120		4534.2	3485.8	223±113
4462.0	3558.0	483±176		4269.3	3750.7	218±78		3588.2	4431.4	229±90
3579.1	4440.9	397±109		3409.8	4610.2	225±90				

E_1+E_2=6823 keV										
E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$		E_1	E_i	$i_{\gamma\gamma}\pm\delta i_{\gamma\gamma}$
5825.4	2194.6	1410±177		5539.7	2480.3	1413±237		5028.7	2991.3	459±144
4982.0	3038.0	378±132		4782.0	3238.0	183±84		4758.9	3261.1	345±135
4637.3	3382.7	525±171		4493.4	3526.6	348±129		4462.0	3558.0	327±120
4418.3	3601.7	681±273		4278.5	3741.5	261±183		3878.4	4141.6	342±117
3612.4	4407.6	414±120		3588.2	4431.8	414±120		3579.1	4440.9	321±108
3289.3	4730.7	303±111								

In general, most of our obtained data are in agreement with data in Ref. [5] and in the ENSDF library [7]. The consistency proves the reliability of the obtained gamma cascade scheme within our work.

Gamma cascade intensity distributions

The gamma cascade intensity distributions of ^{172}Yb determined from all six measured TSC spectra are shown in Fig. 5. The large statistics of counts allow us to determine the gamma cascade intensity distributions over a 250 keV energy interval. This energy interval is twice less than the interval of all 43 investigated nuclei [3]. Therefore, the analysis of the data of ^{172}Yb obtained in the present work is more precise than for all the previous investigated nuclei [3].

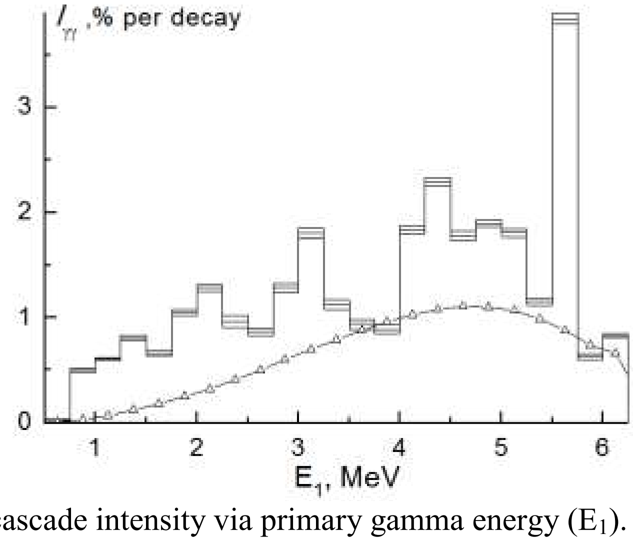

Fig. 5. The gamma cascade intensity via primary gamma energy (E_1). The triangle is $I_{\gamma\gamma}(E_1)$ calculated from the combination of models [8] for nuclear level scheme and [9] for radiative strength function.

In the Fig. 5, the experimental $I_{\gamma\gamma}(E_1)$ is compared with the $I_{\gamma\gamma}(E_1)$ calculated from the combination of nuclear level density [8] and radiative strength function [9] models. There is a clear discrepancy between the experimental $I_{\gamma\gamma}(E_1)$ and that obtained by calculation. Thus, it is needed to use other models for both the nuclear level density and radiative strength function, such as those proposed in Ref. [10].

Conclusion

Within the present work,the gamma cascade intensity distributions of ^{172}Yb was determined for 250 keV energy intervals. Thanks to the large statistics of counts, the obtained data of ^{172}Yb is more precise than any other nuclei, which we have investigated earlier using the Dubna method. The forthcoming studies are to analyze the obtained data here by means of the Dubna method in order to extract the nuclear level density and radiative strength function of ^{172}Yb.

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