Level density and $\gamma$ strength function in $^{162}$Dy from inelastic $^3$He scattering

A. Schiller, M. Guttormsen, E. Melby, J. Rekstad, and S. Siem
Department of Physics, University of Oslo,
P.O.Box 1048, Blindern, N-0316 Oslo, Norway

March 30, 2022

Abstract

Complementary measurements have been performed for the level density and $\gamma$ strength function in $^{162}$Dy using inelastic $^3$He scattering. Comparing these results to previous measurements using the $^{163}$Dy($^3$He,$\alpha$) reaction, reveals that the measured quantities above 1.5 MeV do not depend significantly on the nuclear reaction chosen.

PACS number(s): 21.10.Ma, 21.10.Pc, 25.55.-e, 27.70.+q

1 Introduction

Nuclear level densities have recently gained new interest. When earlier studies of level densities were mainly based on counting levels close to the ground state and neutron resonance spacing at the neutron binding energy $^3$, a variety of new methods and experimental results are available today. A more recent compilation of all existing data on level densities includes level spacing data of several other reactions involving light particles up to $A = 4$ as well as results from Ericson fluctuation measurements. Recently, experimental level densities in $^{69}$As and $^{70}$Ge over a large excitation energy interval of 5-24 MeV have been reported, obtained from proton evaporation spectra of $^{12}$C induced reactions. Also the Oslo cyclotron group has reported on a new method to extract level density and $\gamma$ strength function from primary $\gamma$ spectra (see $^3$ for the basic assumptions and $^3$ for the method). This method has the advantage that the level density is deduced from $\gamma$ transitions, thus the nucleus is likely to be thermalized and the measured level density is supposed to be independent of the formation mechanism of the excited nucleus. Several applications of the method are reported in $^3$. The experimental progress has been accompanied by new theoretical developments, with respect to the first analytical nuclear level density formula proposed by Bethe. Level densities have been studied for finite temperatures.
within the BCS model [12, 13]. Today, Monte Carlo shell model calculations [14, 15] are able to estimate nuclear level densities [16] for heavy mid shell nuclei like $^{162}$Dy [17]. Also more schematic approaches like binomial level densities [18] have been revived lately. Important applications of the theoretical and experimental efforts are calculations of the nucleon synthesis in stars, where the level densities are inputs in large computer codes and thousands of cross sections are estimated [19].

Also the present knowledge of the $\gamma$ strength function is poor. Although the strengths can be roughly calculated by the Weisskopf estimate, which is based on single particle transitions (see e.g. [20]), some transitions deviate many orders of magnitude from this approximation. A compilation of average $\gamma$ transition strengths for dipole and electric quadrupole transitions can be found in [21].

The uncertainty of the $\gamma$ strength function concerns the absolute value and the $\gamma$ energy dependence. For E1 transitions one assumes that the $\gamma$ energy dependence follows the Giant Dipole Resonance (GDR) ($\gamma, \gamma'$) cross section. This is, however, to be proven.

In this work, we determine the level density and the $\gamma$ strength function for $^{162}$Dy for energies close up to the neutron binding energy $B_n$. By comparing the present data, which were obtained from the $^{162}$Dy$(^3$He,$^3$He$'$$\gamma$$)^{162}$Dy reaction, to previous data [22, 23], which were obtained from the $^{163}$Dy$(^3$He,$\alpha\gamma$$)^{162}$Dy reaction, we can test if the basic assumption of our analysis method is fulfilled.

This main assumption is that the $\gamma$ decay pattern from any excitation energy bin is independent of the population mechanism of states within this bin, e.g. direct population by a nuclear reaction, or indirect population by a nuclear reaction followed by one or several $\gamma$ rays. Since the $\gamma$ decay probabilities of an excited state are independent of the populating reaction, the assumption above is generally equivalent to the assumption that the same states are populated equally by the direct and indirect population mechanisms. One can now imagine several cases where this assumption might be invalid.

Firstly, thermalization time might compete with the half life of excited states, and the selectivity of the direct population by a nuclear reaction will be reflected by a different $\gamma$ decay pattern with few and relatively strong $\gamma$ transitions compared to a statistical spectrum which is the expected $\gamma$ decay pattern after complete thermalization.

Secondly, direct population might populate states with different exact or approximate quantum numbers like spin or parity than indirect population. Since states with different exact or approximate quantum numbers do not mix at all or very weakly in the latter case, the ensemble of populated states after thermalization will differ for the two population mechanisms and therefore one can expect different $\gamma$ decay patterns.

It is very difficult to judge where the assumption of the method is applicable and how good this approximation is. Below, we will, by comparing two different direct population mechanisms represented by two different nuclear reactions, investigate in which excitation energy interval the assumption might
2 Experiment and data analysis

The experiment was carried out at the Oslo Cyclotron Laboratory (OCL) using the MC35 Scanditronix cyclotron. The beam current was $\sim 1$ nA of $^3$He particles with an energy of 45 MeV. The experiment was running for a total of 2 weeks. The target was an isotopically enriched 95% $^{162}$Dy self-supporting metal foil with a thickness of 1.4 mg/cm$^2$ glued on an aluminum frame. Particle identification and energy measurements were performed by a ring of 8 Si(Li) telescopes at 45° relative to the beam axis. The telescopes consist of a front and end detector with thicknesses of some 150 $\mu$m and 3000 $\mu$m respectively, which is enough to effectively stop the ejectiles of the reaction. The $\gamma$ rays were detected by a ball of 27 5”×5” NaI(Tl) detectors (CACTUS) covering a solid angle of $\sim 15\%$ of $4\pi$. Three 60% Ge(HP) detectors were used to monitor the selectivity of the reaction and the entrance spin distribution of the product nucleus. During the experiment we collected besides data for the $^{162}$Dy($^3$He,$^3$He$'$)$^{162}$Dy reaction, where results are presented in this work, also data for the $^{162}$Dy($^3$He,$\alpha$)$^{161}$Dy reaction, where some results were presented in [8, 10]. A comprehensive description of the $^{163}$Dy($^3$He,$\alpha\gamma$)$^{162}$Dy experiment, which we will compare our findings to, can be found in [24].

In the first step of the data analysis, the measured ejectile energy is transformed into excitation energy of the product nucleus. In Fig. 1 the raw data are shown. In the next step, the $\gamma$ spectra are unfolded for every excitation energy bin using measured response functions of the CACTUS detector array [25]. In Fig. 2 the unfolded data are shown. In the third step, the primary $\gamma$ spectra for every excitation energy bin are extracted from the unfolded data by the subtraction technique of Ref. [26]. In Fig. 3 the primary $\gamma$ spectra are shown.

In the fourth step, we extract level density and $\gamma$ strength function from the primary $\gamma$ spectra. The main assumption behind this method is the Axel Brink hypothesis [27, 28]

$$\Gamma(E_x, E_\gamma) \propto F(E_\gamma) \varrho(E_f)$$  \hspace{1cm} (1)

with $E_f = E_x - E_\gamma$. It says that the $\gamma$ decay probability in the continuum energy region represented by the primary $\gamma$ spectrum $\Gamma$ is proportional to the level density $\varrho$ and a $\gamma$ energy dependent factor $F$. The level density and the $\gamma$ energy dependent factor are estimated by a least $\chi^2$ fit to the experimental data [6]. In Fig. 4 the experimental data including estimated errors [6] are compared to the fit according to Eq. (1).

The data are fitted very well by the theoretical expression of Eq. (1). This is a remarkable example for the validity of the Axel Brink hypothesis. However, it can never completely be ruled out, that a minor portion of the primary $\gamma$ matrix cannot be factorized into a level density and a $\gamma$ energy dependent factor.
One might also encounter large fluctuations in these quantities at very low level densities around the ground state or when considering highly collective $\gamma$ transitions and single particle $\gamma$ transitions at similar $\gamma$ energies. Since the least $\chi^2$ fit according to Eq. (1) yields an infinitely large number of equally good solutions, which can be obtained by transforming one arbitrary solution by

$$\tilde{q}(E_x - E_\gamma) = q(E_x - E_\gamma) A \exp(\alpha [E_x - E_\gamma]) \quad (2)$$

and

$$\tilde{F}(E_\gamma) = F(E_\gamma) B \exp(\alpha E_\gamma) \quad (3)$$

we have to determine the three parameters $A$, $B$ and $\alpha$ of the transformation by comparing the results to other experimental data. We fix the parameters $A$ and $\alpha$ by comparing the extracted level density curve to the number of known levels per excitation energy bin around the ground state [29] and to the level density at the neutron binding energy $B_n$ calculated from neutron resonance spacing data [30]. Since the procedure is described in detail in Ref. [6], we only show in Fig. 5 how the extracted level density curve compares to other experimental data.

The parameter $B$ could now in principle be fixed by comparing the extracted $\gamma$ energy dependent factor $F$ to other experimental data of the $\gamma$ strength function. However since data are very sparse and the absolute normalization of $\gamma$ strength function data is very uncertain, we give the $\gamma$ energy dependent factor in arbitrary units.

## 3 Results and discussion

### 3.1 The level density

We compare extracted level densities of $^{162}$Dy from two reactions, namely $^{162}$Dy($^3$He,$^3$He'\,$\gamma$)\,$^{162}$Dy and $^{163}$Dy($^3$He,\,$\alpha\gamma$)\,$^{162}$Dy. While level densities from the latter reaction were already published in [4, 22, 7] using approximate extraction methods, and in [3] in the present form, data from the first reaction are shown here for the first time. Figure 6 shows the relative level densities, which are calculated by dividing the extracted level densities by an exponential $C \exp(E/T)$ with $T = 580$ keV and $C = 10$ MeV$^{-1}$ in our case. One can see that both level densities agree very well within 10\% in the excitation energy interval 1.5 MeV to 6.5 MeV. This result is very encouraging, since level densities are generally only known within an error of ±50-100\%. Above 6.5 MeV the errors are too large in order to make conclusive observations. Below ~1.5 MeV the two level densities differ dramatically from each other. In Fig. 5 one can see that the extracted level density from the $^{163}$Dy($^3$He,\,$\alpha\gamma$)\,$^{162}$Dy reaction agrees very well with the number of known levels per excitation energy bin below ~1.2 MeV, whereas the extracted level density from the $^{162}$Dy($^3$He,$^3$He'\,$\gamma$)\,$^{162}$Dy reaction overestimates the number of levels in this energy region by a factor of ~3.
The level density at $\sim 0.5$ MeV of excitation energy is determined by the data in the primary $\gamma$ matrix which lie approximately on the diagonal $E_x \sim E_\gamma$ (see Fig. 3). Careful examination of Fig. 4 shows, that the bumps at $E_x \sim E_\gamma$ are very well fitted by the factorization given by Eq. (1). We therefore conclude, that the differences in level density around $\sim 0.5$ MeV of excitation energy are not artifacts of the extraction method, but have their origin in differences of the primary $\gamma$ spectra. We actually find in the primary $\gamma$ matrix of the $^{162}$Dy($^3$He,$^3$He'\gamma)$^{162}$Dy reaction a large number of high energetic $\gamma$ transitions, connecting the direct populated states with the ground state rotational band. This surplus of counts compared to primary $\gamma$ spectra from the $^{163}$Dy($^3$He,\alpha\gamma)$^{162}$Dy reaction is the reason for overestimating the level density at $\sim 0.5$ MeV of excitation energy.

We argue that the level density curve extracted from the neutron pick up reaction data is the more realistic one, as supported by Fig. 5. Since the neutron pick up reaction cross section is dominated by high $l$ neutron transfer, the direct population of the $^{162}$Dy nucleus takes place through one particle one hole components of the wave functions. Such configurations are not eigenstates of the nucleus, but they are rather distributed over virtually all eigenstates in the neighboring excitation energy region. Thus, we can expect fast and complete thermalization before $\gamma$ emission. The inelastic $^3$He scattering on the other hand is known to populate mainly collective excitations. These collective excitations will thermalize rather slowly, since their structure is much more like eigenstates of the nucleus, and their wave functions are less spread over eigenfunctions in the close excitation energy region. However, we can expect that their structure is similar to the structure of states in the ground state rotational band. Therefore, the large $\gamma$ transition rates from the direct populated states to the ground state rotational band might just reflect the inverse process of inelastic scattering. The surplus of $\gamma$ counts can therefore be interpreted as preequilibrium decay. An extreme example for this are nuclear resonance fluorescence studies (NRF) [31]. It is estimated, that in even even nuclei more than 90% of the $\gamma$ strength from states excited by $\gamma$ rays is going to the ground state or to the first excited state. Thermalization of the excited states in NRF is also hindered by the fact that one populates isovector states, which in the proton neutron interacting boson model (IBA-2) are characterized by a different (approximate) $F$ spin quantum number than other states in the same excitation energy regions.

We would like to point out, that although the basic assumption behind the primary $\gamma$ method is partially violated in the case of the $^{162}$Dy($^3$He,$^3$He'\gamma)$^{162}$Dy reaction, the level densities in the excitation energy interval 1.5 MeV to 6.5 MeV deduced from the two reactions agree extremely well. This indicates, that the extracted level density curves are quite robust with respect to the goodness of the assumption. Especially the bump at $\sim 2.5$ MeV excitation energy indicating the breaking of nucleon pairs [7, 10] and the quenching of pairing correlations [8] could be very well reproduced. One should also keep in mind that the
two reactions populate states with slightly different spin distributions due to
the different target spins in the two reactions, which might account for some
differences in the extracted level densities.

3.2 The $\gamma$ energy dependent factor

We compare the extracted $\gamma$ energy dependent function $F$ of $^{162}\text{Dy}$ for the two
reactions. The $F$ function from the $^{161}\text{Dy} (^{3}\text{He},\alpha\gamma)^{162}\text{Dy}$ reaction was already
published in [22] using an approximate extraction method, however the data
were reanalyzed using the exact extraction method of Ref. [6] and are in the
present form, as well as data from the $^{162}\text{Dy} (^{3}\text{He},^{3}\text{He}'\gamma)^{162}\text{Dy}$ reaction, published for the first time in this work. Figure 7 shows the relative $F$ functions,
which are obtained by dividing the extracted $F$ function by $E_{\gamma}^n$ with $n = 4.3$
and scaling them to $\sim 1$ at $\sim 4$ MeV of $\gamma$ energy. Also in this case the two
functions agree within 10% in the $\gamma$ energy interval of 1.5 MeV to 6.5 MeV.
Above $\sim 6.5$ MeV again, the error bars are too large in order to allow for any
conclusions. Below $\sim 1.3$ MeV of $\gamma$ energy, the two functions differ dramatically
from each other. Due to experimental difficulties, like ADC threshold walk and
bad timing properties of low energetic $\gamma$ rays, we had to exclude $\gamma$ rays with
energies below 1 MeV from the data analysis [6]. It is therefore very difficult to
judge if the differences in the $F$ function curves below 1.5 MeV of $\gamma$ energy are
also due to experimental problems (i.e. the experimental cut was too optimistic,
and we should rather have excluded all $\gamma$ rays with energies below 1.5 MeV) or
due to the different nuclear reactions used to excite the $^{162}\text{Dy}$ nucleus.

Also here we would like to emphasize, that despite the basic assumption
behind the primary $\gamma$ method is not completely fulfilled in the case of the
$^{162}\text{Dy} (^{3}\text{He},^{3}\text{He}'\gamma)^{162}\text{Dy}$ reaction, the two $F$ functions agree very well. Especially
the bump at $\sim 2.5$ MeV of $\gamma$ energy, which we interpret as a Pigmy Resonance
is equally pronounced in both reactions. We are therefore very confident that
the extracted level density and $\gamma$ energy dependent factor for $^{162}\text{Dy}$ presented
in this work are not, or very little, reaction dependent.

4 Conclusions

This work compares the results from the $^{162}\text{Dy} (^{3}\text{He},^{3}\text{He}'\gamma)^{162}\text{Dy}$ reaction to
those of the $^{163}\text{Dy} (^{3}\text{He},\alpha\gamma)^{162}\text{Dy}$ reaction. The level density $\varrho$ and the $\gamma$ energy
dependent factor $F$ in $^{162}\text{Dy}$ are shown to be reliably extracted with our method
in the energy interval 1.5-6.5 MeV. The findings are independent of the particular
reaction chosen to excite the $^{162}\text{Dy}$ nucleus. The two reactions differ from
each other (i) in the reaction type; i.e. inelastic $^{3}\text{He}$ scattering versus neutron pick up, and thus in the nuclear states populated before thermalization, namely
collective excitations versus one particle one hole states, (ii) in the target spins;
$0^+$ for $^{162}\text{Dy}$ versus $5/2^-$ for $^{163}\text{Dy}$, and thus in the spin distribution of direct
populated states, and (iii) in the $Q$-value; 0 MeV for inelastic $^3$He scattering versus 14.3 MeV for the neutron pick up reaction. Nevertheless, the only differences in the extracted quantities are those in the level densities below $\sim$1.5 MeV of excitation energy. These might be explained by preequilibrium $\gamma$ decay in the $^{162}$Dy($^3$He,$^3$He'\$\gamma$)$^{162}$Dy reaction, whereas the $^{163}$Dy($^3$He,\alpha\gamma$)^{162}$Dy reaction is supposed to show only equilibrium $\gamma$ decay, and thus reveals reliable level densities below 1.5 MeV of excitation energy, which is supported by comparison to known data. However, although preequilibrium $\gamma$ decay violates the basic assumption of the primary $\gamma$ method, the effect on the extracted level density $\rho$ and the $\gamma$ energy dependent factor $F$ between 1.5 MeV and 6.5 MeV of energy is shown to be less than 10%. In conclusion, the present results have given further confidence in the new extraction techniques, and open for several interesting applications in the future.

The preequilibrium decay does not seem to violate the Axel Brink hypothesis, since the respective parts of the primary $\gamma$ spectrum could be fitted within this assumption. However, the extracted quantities $\rho$ and $F$ will then only represent a weighted sum of the respective quantities obtained from preequilibrium and equilibrium $\gamma$ decay, where in the case of the $^{162}$Dy($^3$He,$^3$He'\$\gamma$)$^{162}$Dy reaction, the preequilibrium process dominates the level density below 1.5 MeV of excitation energy. We conclude therefore that neutron pick up reactions are more suitable than inelastic $^3$He scattering for our method, since the states populated by the former reaction presumably thermalize completely, whereas those populated by the latter reaction might not completely thermalize before $\gamma$ emission.

5 Acknowledgments

The authors wish to thank Jette Sørensen for making the target and E.A. Olsen and J. Wikne for excellent experimental conditions. Financial support from the Norwegian Research Council (NFR) is gratefully acknowledged.
References

[1] A. Gilbert and A.G.W. Cameron, Can. J. Phys. 43, 1446, (1965)

[2] T. von Egidy, H.H. Schmidt, and A.N. Behkami, Nucl. Phys. A481, 189 (1988)

[3] A.S. Iljinov, M.V. Mebel, N. Bianchi, E. De Sanctis, C. Guaraldo, V. Lucherini, V. Muccifora, E. Polli, A.R. Reolon, and P. Rossi, Nucl. Phys. A543, 517 (1992)

[4] U.K. Pal, D.R. Chakrabarty, V.M. Datar, Suresh Kumar, E.T. Mirgule, and H.H. Oza, J. Phys. G 25, 1671 (1999)

[5] L. Henden, L. Bergholt, M. Guttormsen, J. Rekstad, and T.S. Tvedter, Nucl. Phys. A589, 249 (1995)

[6] A. Schiller, L. Bergholt, M. Guttormsen, E. Melby, J. Rekstad, and S. Siem, Nucl. Instrum. Methods (to be published)

[7] E. Melby, L. Bergholt, M. Guttormsen, M. Hjorth-Jensen, F. Ingebritsen, S. Messelt, J. Rekstad, A. Schiller, S. Siem, and S.W. Ødegård, Phys. Rev. Lett. 83, 3150 (1999)

[8] A. Schiller, A. Bjerve, M. Guttormsen, M. Hjorth-Jensen, F. Ingebritsen, E. Melby, S. Messelt, J. Rekstad, S. Siem, and S.W. Ødegård, preprint nucl-ex/9909011

[9] M. Guttormsen, M. Hjorth-Jensen, E. Melby, J. Rekstad, A. Schiller, and S. Siem, preprint nucl-ex/9910018

[10] M. Guttormsen, A. Bjerve, M. Hjorth-Jensen, E. Melby, J. Rekstad, A. Schiller, S. Siem, and A. Belic, preprint nucl-ex/9911011

[11] H.A. Bethe, Phys. Rev. 50, 332 (1936)

[12] M. Sano and S. Yamasaki, Prog. Theor. Phys. 29, 397 (1963)

[13] Nguyen Dinh Dang, Z. Phys. A335, 253 (1990)

[14] G.H. Lang, C.W. Johnson, S.E. Koonin, and W.E. Ormand, Phys. Rev. C48, 1518 (1993)

[15] S.E. Koonin, D.J. Dean, and K. Langanke, Phys. Rep. 278, 1 (1997)

[16] W.E. Ormand, Phys. Rev. C56, R1678 (1997)

[17] J.A. White, S.E. Koonin, and D.J. Dean, preprint nucl-th/9812044

[18] A.P. Zuker, preprint nucl-th/9910002
[19] S. Goriely, Nucl. Phys. A605, 28 (1996)

[20] A. Bohr and B.R. Mottelson, Nuclear Structure, (W.A. Benjamin, Inc., New York, Amsterdam, 1969), Vol. I, p. 389

[21] W. Zipper, F. Seiffert, H. Grawe, and P. von Brentano, Nucl. Phys. A551, 35 (1993)

[22] T.S. Tveter, L. Bergholt, M. Guttormsen, E. Melby, and J. Rekstad, Phys. Rev. Lett. 77, 2404 (1996)

[23] M. Guttormsen, A. Atac, G. Løvhøiden, S. Messelt, T. Ramsøy, J. Rekstad, T.F. Thorsteinsen, T.S. Tveter, and Z. Zelazny, Physica Scripta T32, 54 (1990)

[24] M. Guttormsen, L. Bergholt, F. Ingebretsen, G. Løvhøiden, S. Messelt, J. Rekstad, T.S. Tveter, H. Helstrup, and T.F. Thorsteinsen, Nucl. Phys. A573, 130 (1994)

[25] M. Guttormsen, T.S. Tveter, L. Bergholt, F. Ingebretsen, and J. Rekstad, Nucl. Instrum. Methods A374, 371 (1996)

[26] M. Guttormsen, T. Ramsøy, and J. Rekstad, Nucl. Instrum. Methods A255, 518 (1987)

[27] D.M. Brink, Ph.D. thesis, Oxford University, 1955

[28] P. Axel, Phys. Rev. 126, 671 (1962)

[29] R.B. Firestone and V.S. Shirley, Table of Isotopes, 8th edition, (John Wiley & Sons, Inc., New York, Chichester, Brisbane, Toronto, Singapore, 1996), Vol. II

[30] H.I. Liou, G. Hacken, J. Rainwater, and U.N. Singh, Phys. Rev. C11, 462 (1975)

[31] C. Wesselborg, P. von Brentano, K.O. Zell, R.D. Heil, H.H. Pitz, U.E.P. Berg, U. Kneissl, S. Lindenstruth, U. Seemann, and R. Stock, Phys. Lett. B207, 22 (1988)
Figure 1: Raw data of the $^{162}\text{Dy}(^{3}\text{He},^{3}\text{He'}\gamma)^{162}\text{Dy}$ reaction. Some $\gamma$ spectra for different excitation energies are projected out on the right hand side.

Figure 2: Unfolded data of the $^{162}\text{Dy}(^{3}\text{He},^{3}\text{He'}\gamma)^{162}\text{Dy}$ reaction. Also here, some $\gamma$ spectra for different excitation energies are projected out on the right hand side.
Figure 3: Primary $\gamma$ spectra of the $^{162}$Dy($^{3}$He,$^{3}$He'\ $\gamma$)$^{162}$Dy reaction. Here again, some $\gamma$ spectra for different excitation energies are projected out on the right hand side.
Figure 4: Normalized primary $\gamma$ spectra for the $^{162}$Dy($^3$He,$^3$He'\$\gamma$)$^{162}$Dy reaction including estimated errors (data points) compared to the least $\chi^2$ fit according to Eq. (1) (lines).
Figure 5: Determination of parameters $A$ and $\alpha$ of Eq. (3). The extracted level density curve from the $^{162}$Dy($^3$He,$^3$He'\gamma)$^{162}$Dy reaction data (full data points and line in insert) is compared to the number of known levels per excitation energy bin around the ground state (histogram) in the region between the arrows, and to the level density at the neutron binding energy $B_n$, calculated from neutron resonance spacing data (square in insert). In comparison, the extracted level density curve from the $^{163}$Dy($^3$He,\alpha\gamma)$^{162}$Dy reaction data (empty data points and slashed line in insert) is shown.
Figure 6: Comparison of the extracted relative level density of $^{162}\text{Dy}$ deduced from the $^{162}\text{Dy}(^3\text{He},^3\text{He}'\gamma)^{162}\text{Dy}$ reaction (this work) and from the $^{163}\text{Dy}(^3\text{He},\alpha\gamma)^{162}\text{Dy}$ reaction (previous works). The error bars of the former level density curve are about half of the errors of the latter due to $\sim 5$ times better statistics in the data of the $^{162}\text{Dy}(^3\text{He},^3\text{He}'\gamma)^{162}\text{Dy}$ reaction. The differences between the two curves below 1.5 MeV of excitation energy are accounted for in the text.
Figure 7: Comparison of the extracted relative $\gamma$ energy dependent function of $^{162}$Dy deduced from the $^{162}$Dy($^3$He,$^3$He$\gamma$)$^{162}$Dy (this work) and from the $^{163}$Dy($^3$He,$\alpha\gamma$)$^{162}$Dy reaction (previous work, reanalyzed in this work). Also here, the error bars of the relative $\gamma$ energy dependent function extracted from the data of the former reaction are about half of the other ones, due to better statistics.