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

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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.

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## I. INTRODUCTION

Nuclear level densities have recently gained new interest. While 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 [1,2], a variety of new methods and experimental results are available today. More recent compilations of existing data on level densities [3,4] include 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 [5], obtained from proton evaporation spectra of $^{12}$C-induced reactions. Also, the Oslo cyclotron group has reported on a new method to extract level densities and $\gamma$ strength functions from primary $\gamma$ spectra (see Ref. [6] for the basic assumptions, and Ref. [7] 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 were reported in Refs. [8–11].

Experimental progress has been accompanied by new theoretical developments with respect to the first analytical nuclear level density formula proposed by Bethe [12]. Level densities have been studied for finite temperatures within the BCS model [13,14]. Today, Monte Carlo shell model calculations [15,16] are able to estimate nuclear level densities [17] for heavy midshell nuclei like $^{162}$Dy [18]. Also, more schematic approaches like binomial level densities [19] 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 [20]. Another aspect studied is the reduction of the $\omega$ mass with temperature [21], and as a consequence the reduction of the level density parameter $a \propto m^*$, where the effective mass $m^*$ is given by $m_k m_\omega / m$. This is believed to have an appreciable effect on the physics of stellar collapse.

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., Ref. [22]), 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 Ref. [23]. 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 $(\gamma,\gamma')$ cross section. However, this is to be proven.

In this work, we determine the level density and $\gamma$ 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 [24,9], 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 direct and indirect population mechanisms. One can now imagine several cases where this assumption might be invalid.

First, 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.

Second, 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 mix very weakly in the latter case, the ensemble of populated states after thermalization will differ for the two population mechanisms; 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,

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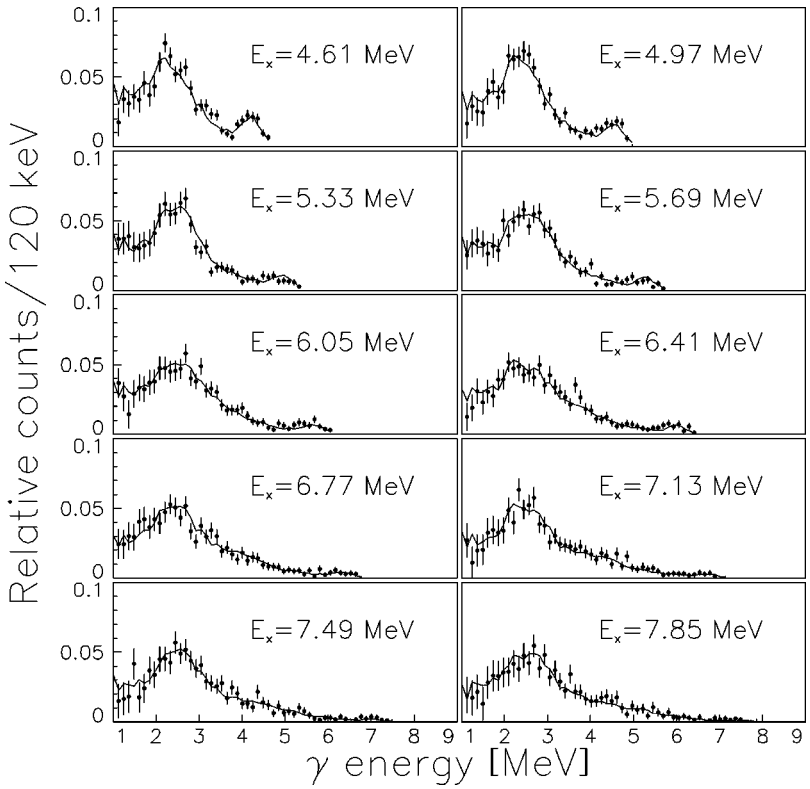


FIG. 1. Normalized primary $\gamma$ spectra for the $^{162}$Dy($^3$He,$^3$He$'\gamma$)$^{162}$Dy reaction, including estimated errors (data points) compared to the least $\chi^2$ fit according to Eq. (1) (lines).

investigate in which excitation energy interval the assumption might break down.

## II. EXPERIMENT AND DATA ANALYSIS

The experiment was carried out at the Oslo Cyclotron Laboratory 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 two 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 eight Si(Li) telescopes at 45° relative to the beam axis. The telescopes consist of a front and end detector with thicknesses of some 150 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 in$\times$5 in NaI(Tl) detectors (CACTUS) [25] 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 also collected, besides data for the $^{162}$Dy($^3$He,$^3$He$'$)$^{162}$Dy reaction, where results are presented in this work, data for the $^{162}$Dy($^3$He,$\alpha$)$^{161}$Dy reaction, where some results were presented in Refs. [9,11]. A comprehensive description of the $^{163}$Dy($^3$He,$\alpha\gamma$)$^{162}$Dy experiment, to which we will compare our findings, can be found in Ref. [26].

In the first step of the data analysis, the measured ejectile energy is transformed into the excitation energy of the product nucleus. In the second step, the $\gamma$ spectra are unfolded for every excitation energy bin using measured response functions of the CACTUS detector array [27]. 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. [28]. In the fourth step, we extract the level density and $\gamma$ strength function from the primary $\gamma$ spectra. The main assumption behind this method is the Axel-Brink hypothesis [29,30]

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

with $E_f=E_x-E_\gamma$. This states 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 [7]. In Fig. 1 the experimental data, including estimated errors [7], 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 be completely 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.

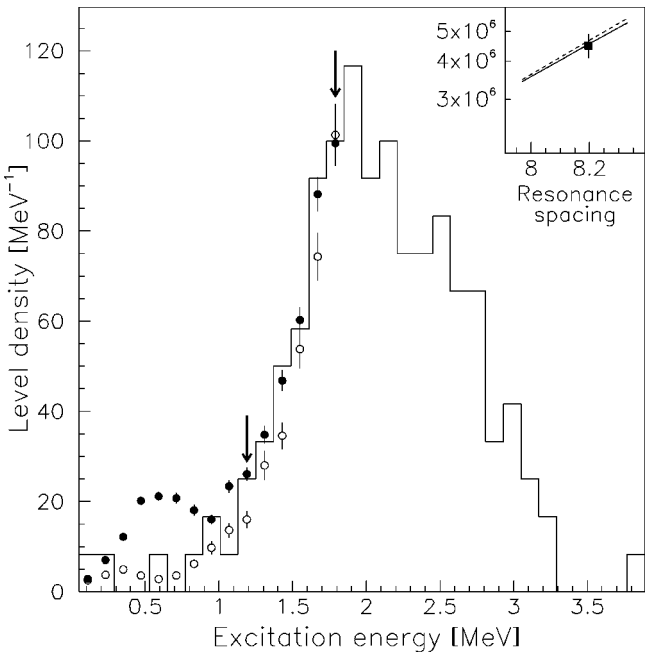


FIG. 2. Determination of parameters $A$ and $\alpha$ of Eq. (2). The extracted level density curve from the $^{162}$Dy($^3$He,$^3$He$'\gamma$)$^{162}$Dy reaction data (full data points and line in the inset) is compared to the number of known levels per excitation energy bin around the ground state (histogram) 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 the inset). 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 the inset) is shown.

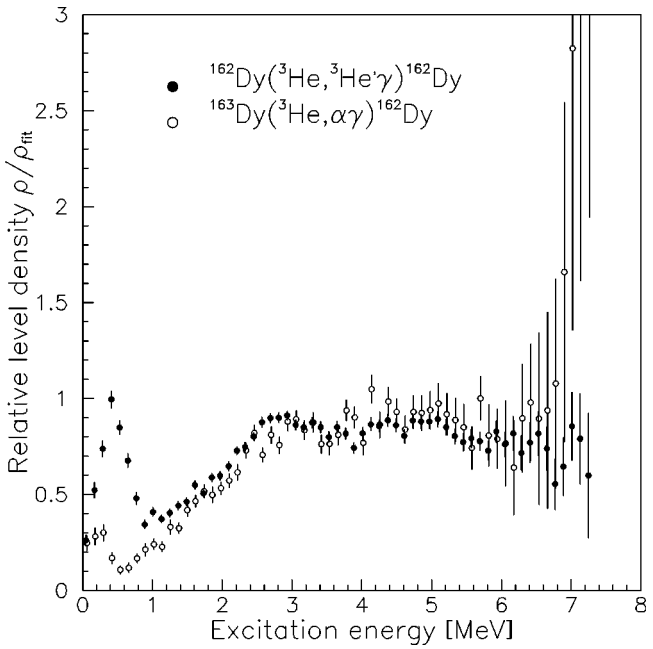


FIG. 3. Comparison of the extracted relative level density of $^{162}$Dy deduced from the $^{162}$Dy($^3$He,$^3$He$'\gamma$)$^{162}$Dy reaction (this work) and from the $^{163}$Dy($^3$He,$\alpha\gamma$)$^{162}$Dy reaction (previous works). The error bars of the former level density curve are about half the number of the error bars of the latter due to $\sim$5 times better statistics in the data of the $^{162}$Dy($^3$He,$^3$He$'\gamma$)$^{162}$Dy reaction. The differences between the two curves below 1.5-MeV excitation energy are accounted for in the text.

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

$$\tilde{\varrho}(E_x-E_\gamma)=\varrho(E_x-E_\gamma)\,A\exp(\alpha[E_x-E_\gamma]), \qquad (2)$$

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

[7], 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 [31], and to the level density at the neutron binding energy $B_n$ calculated from neutron resonance spacing data [32]. Since the procedure was described in detail in Ref. [7], in Fig. 2 we only show 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.

## III. RESULTS AND DISCUSSION

### A. 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 Refs. [6,24,8] using approximate extraction methods, and in Ref. [9] in the present form, data from the first reaction are shown here for the first time. Figure 3 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 1.5–6.5 MeV. This result is very encouraging, since level densities are generally only known within an error of $\pm$50–100 %. Above 6.5 MeV the errors are too large to make conclusive observations. Below $\sim$1.5 MeV the two level densities differ dramatically from each other. In Fig. 2 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 $\sim$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 $\sim$3.

The level density at $\sim$0.5 MeV excitation energy is determined by the data in the primary $\gamma$ matrix which lie approximately on the diagonal $E_x \gtrsim E_\gamma$. Careful examination of Fig. 1 shows that the bumps at $E_x \gtrsim E_\gamma$ are very well fitted

by the factorization given by Eq. (1). We therefore conclude that the differences in the level density at excitation energies around ~0.5 MeV are not artifacts of the extraction method, but have their origin in differences of the primary $\gamma$ spectra. In the primary $\gamma$ matrix of the $^{162}$Dy($^{3}$He,$^{3}$He$'\gamma$)$^{162}$Dy reaction we actually find 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 ~0.5 MeV of excitation energy.

We argue that the level density curve extracted from the neutron pickup reaction data is the more realistic one, as supported by Fig. 2. Since the neutron pickup 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 are rather distributed over virtually all eigenstates in the neighboring excitation energy region. Thus we can expect fast and complete thermalization before $\gamma$ emission. 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 (NRF) studies [33]. It is estimated that in even nuclei more than 90% of the $\gamma$ strength from states excited by $\gamma$ rays goes 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 1.5–6.5 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 ~2.5-MeV excitation energy, indicating the breaking of nucleon pairs [8,11] and the quenching of pairing correlations [9], 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.

### B. $\gamma$-energy-dependent factor

We compare the extracted $\gamma$-energy-dependent function $F$ of $^{162}$Dy for the two reactions. The $F$ function from the

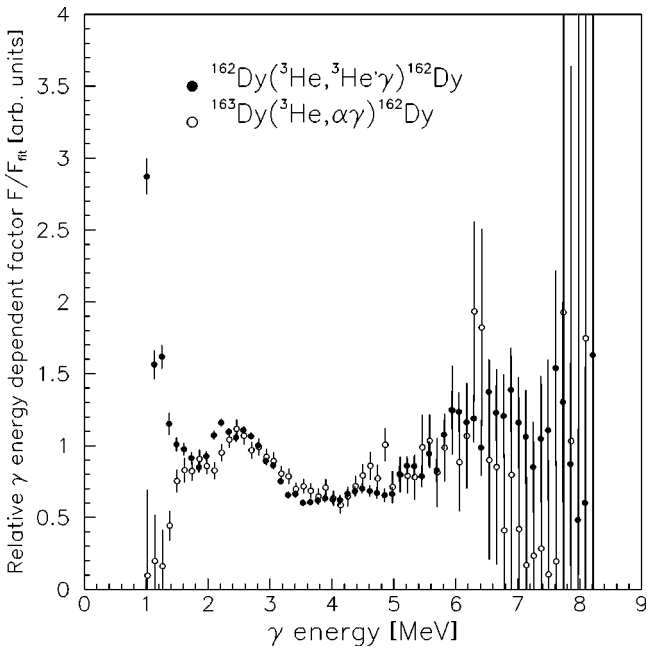


FIG. 4. Comparison of the extracted relative $\gamma$-energy-dependent function of $^{162}$Dy deduced from the $^{162}$Dy($^{3}$He,$^{3}$He$'\gamma$)$^{162}$Dy (this work) and from the $^{163}$Dy($^{3}$He,$\alpha\gamma$)$^{162}$Dy reaction (previous work, reanalyzed in this work). Also here, the error bars of the relative $\gamma$-energy-dependent function extracted from the data of the former reaction are about half the number of the other ones, due to better statistics.

$^{163}$Dy($^{3}$He,$\alpha\gamma$)$^{162}$Dy reaction was already published in Ref. [24] using an approximate extraction method; however, the data were reanalyzed using the exact extraction method of Ref. [7], and are, along with data from the $^{162}$Dy($^{3}$He,$^{3}$He$'\gamma$)$^{162}$Dy reaction, published in the present form for the first time in this work. Figure 4 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 ~1 at ~4 MeV $\gamma$ energy. Also in this case the two functions agree within 10% in the $\gamma$ energy interval 1.5–6.5 MeV. Above ~6.5 MeV again, the error bars are too large to allow for any conclusions. Below ~1.3 MeV $\gamma$ energy, the two functions differ dramatically from each other. Due to experimental difficulties, like Analog Digital Converter (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 [7]. It is therefore very difficult to judge if the differences in the $F$ function curves below 1.5 MeV $\gamma$ 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 to the different nuclear reactions used to excite the $^{162}$Dy nucleus.

Here we would also like to emphasize that, though the basic assumption behind the primary $\gamma$ method is not completely fulfilled in the case of the $^{162}$Dy($^{3}$He,$^{3}$He$'\gamma$)$^{162}$Dy reaction, the two $F$ functions agree very well. In particular the bump at ~2.5 MeV $\gamma$ energy, which we interpret as a ''pigmy resonance,'' is equally pronounced in both reac-

tions. We are therefore very confident that the extracted level density and $\gamma$-energy-dependent factor for $^{162}$Dy presented in this work are not, or are only very slightly, reaction dependent.

## IV. CONCLUSIONS

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

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