# Systematic study of the fragmentation of low-lying dipole strength in odd-*A* rare earth nuclei investigated in nuclear resonance fluorescence experiments

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(Received 18 June 1996)

Nuclear resonance fluorescence experiments were performed on the rare earth nuclei $^{155}$Gd and $^{159}$Tb to study the fragmentation of the $M1$ *scissors mode* in *odd* deformed nuclei and to establish a kind of systematics. Using the bremsstrahlung photon beam of the Stuttgart Dynamitron (end point energy 4.1 MeV) and high resolution Ge-$\gamma$ spectrometers detailed information was obtained on excitation energies, decay widths, transition probabilities, and branching ratios. The results are compared to those observed recently for the neighboring odd nuclei $^{161,163}$Dy and $^{157}$Gd. Whereas in the odd Dy isotopes the dipole strength is rather concentrated, both Gd isotopes show a strong fragmentation of the strength into about 25 ($^{155}$Gd) and 90 transitions ($^{157}$Gd) in the energy range 2–4 MeV. The nucleus $^{159}$Tb linking the odd Dy and Gd isotopes exhibits an intermediate strength fragmentation. In general the observed total strength in the odd nuclei is reduced by a factor of 2–3 as compared to their neighboring even-even isotopes. The different fragmentation behavior of the dipole strengths in the odd Dy and Gd isotopes is unexplained up to now. [S0556-2813(96)03311-0]

PACS number(s): 25.20.Dc, 21.10.Re, 23.20.−g, 27.70.+q

## I. INTRODUCTION

In recent years many investigations have been devoted to the study of the systematics and the fragmentation of the low-lying orbital $M1$ mode in deformed even-even nuclei, often referred to as the *scissors mode*. The discovery of this new type of excitation by Bohle *et al.* [1] led to an increased interest in low-lying dipole excitations in heavy nuclei and stimulated a flock of both theoretical studies and experimental investigations using different probes like photons, electrons, and protons (see [2] and references therein). For even-even nuclei the scissors mode nowadays is well established as a rather general phenomenon in deformed nuclei over the whole mass region. The nuclear resonance fluorescence (NRF) technique has proved to be the most sensitive and selective probe to study this mode and in particular its strength fragmentation (see [3] and references therein).

It is a principal and interesting question whether the scissors mode exists in odd-mass nuclei as a common feature as in even-even deformed nuclei. Even if scissors mode states are much more difficult to observe and to identify in odd-mass than in even-even nuclei, as discussed later, there is another compelling argument to investigate systematically the odd-mass case. Up to now there has been nearly no information on the bands built on the scissors mode. In NRF experiments on deformed even-even nuclei only the $J^\pi=1^+$ states are excited, which are conjectured to be the bandhead of a $K^\pi=1^+$ band, because for the excitation of the second level of the band from the ground state an $E2$ transition is needed, which has a much lower intensity in photon scattering. In odd-mass nuclei, in contrast, $M1$ excitations from the ground state can lead, in general, to the bandhead as well as to other members of a single scissors mode band. A detailed experimental study of the scissors mode states in odd-mass nuclei can thus shed light on their band structure and perhaps once and for all settle the question of the collectivity of these states.

The coupling of an unpaired nucleon to the excitations in the even-even core of odd-*A* rare earth nuclei has been studied theoretically by Van Isacker and Frank in the framework of the interacting boson-fermion model (IBFM) [4,5], by Raduta and co-workers [6,7] in the particle-core-coupling model, and quite recently by Soloviev *et al.* [8] within the quasiparticle-phonon-nuclear model (QPNM). All these calculations predict a *splitting*, a distribution of the orbital $M1$ strength over a large number of excitations due to the different couplings of the unpaired nucleon to *each* of the orbital $M1$ excitations in the even-even core and due to the mixing with single-particle levels.

The investigation of the orbital $M1$ mode in odd-*A* nuclei in NRF experiments has to deal with some drawbacks inherent to these odd-mass nuclei. The angular distributions for most spin cascades involved in excitation and deexcitation of the nuclear levels become nearly isotropic, due to the half-integer spins of both the ground and excited states. In general, unambiguous spin assignments to the excited states are therefore no longer possible. Only in few favorable cases can the spin of the excited state be determined from the measured angular distribution with the sensitivity of present NRF setups (e.g., for ground-state spin $J_0=1/2$; see Ref. [9]). In addition the half-integer spins also cause the transitions to be nearly unpolarized and thus one cannot extract parities from NRF polarization measurements.

Besides these principal physical drawbacks another more experimental problem arises in the case of odd-*A* nuclei. It is related to the strong fragmentation of dipole strength. The

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TABLE I. Target compositions and specifications.

| Isotope | Composition | Enrichment [%] | Total masses [mg] Isotope | $^{27}$Al | Major impurities |
|---|---|---|---|---|---|
| $^{155}$Gd | $Gd_2O_3$ | 92.8 | 919 | 759 | $^{156}$Gd (5.7%); $^{157}$Gd (0.8%) |
| $^{157}$Gd | $Gd_2O_3$ | 92.3 | 1850 | 510 | $^{158}$Gd (5.4%); $^{156}$Gd (1.9%) |
| $^{159}$Tb | $Tb_4O_7$ | 99.9 | 1655 | 508 | $Dy_2O_3$; $Gd_2O_3$ ($\leqslant$ 0.1%) |

effect of the resulting much smaller peaks for excitations in odd-*A* nuclei as compared to the even-even nuclei is twofold. First, since the background from nonresonant scattering of the incident bremsstrahlung beam remains the same as in even-even nuclei, the NRF measurements on odd-*A* nuclei require a much higher experimental sensitivity. Furthermore, even small amounts of impurities ($\leqslant$2%) of the neighboring even-even isotopes give rise to peaks in the photon scattering spectra, which are comparable in size to the strongest peaks for excitations in the odd-*A* isotopes. This shows the necessity of targets with the highest available enrichment. Furthermore, the excitations in the neighboring even-even nuclei have to be well known.

The first NRF experiment searching for the scissors mode in an odd-*A* nucleus was performed on the odd-proton nucleus $^{165}$Ho by the Darmstadt group [10]. However, no strong excitation [$B(M1)\uparrow \geqslant 0.1\ \mu_N^2$] could be observed. Our group detected for the first time a concentration of dipole strength around 3 MeV in the odd-neutron isotope $^{163}$Dy [11], which nicely fits into the systematics of the strong orbital $M1$ excitations in the neighboring even-even Dy isotopes $^{160,162,164}$Dy [12–14].

The interpretation of the dipole excitations observed in $^{163}$Dy as scissors mode excitations was supported by calculations in the framework of the IBFM model [11]. A similar behavior subsequently was seen in our measurements on $^{161}$Dy [14]. However, the picture observed in the Dy isotopic chain changed dramatically in the Gd isotope $^{157}$Gd. In $^{157}$Gd no concentration of dipole strength could be detected. On the contrary, the excitations were spread over the entire energy region from 1.9 to 4 MeV (about 90 transitions) [14].

The aim of the present experiments was to study the other stable odd Gd isotope $^{155}$Gd, completing the investigations of the Gd isotopic chain ($^{154,155,156,157,158,160}$Gd) [1,13–19] in order to see whether the extreme fragmentation of the dipole strength in $^{157}$Gd represents some ''pathological'' case or whether the observed concentration of dipole strength in $^{161,163}$Dy is the exception. In addition, it was of interest to investigate the odd-proton nucleus $^{159}$Tb which links the Gd and Dy isotopic chains. After a brief survey on the well-known experimental technique of the NRF and the theoretical relations needed for the understanding of the extracted quantities (Sec. II) the results are presented in Sec. III. Section IV deals with the discussion of the new results for $^{155}$Gd and $^{159}$Tb in the context of the previous observations in $^{161,163}$Dy and $^{157}$Gd and recent calculations.

## II. EXPERIMENTAL METHOD

### A. Experimental setup

All data reported on were obtained in NRF experiments performed at the well-established bremsstrahlung facility of the Stuttgart Dynamitron accelerator [20]. The bremsstrahlung endpoint energy in the experiments was 4.1 MeV. The scattered photons were detected by three high-resolution Ge(HP)-$\gamma$ spectrometers of high efficiencies $\epsilon$ ranging from $\epsilon \approx$ 25% to $\epsilon \approx$ 100% relative to a standard 3''$\times$3'' NaI/Tl detector. The detectors were installed at scattering angles of approximately 90°, 127°, and 150° with respect to the incident bremsstrahlung beam. Details of the experimental setup were described in our previous publications [3,14,17]. Table I summarizes the target compositions and specifications.

### B. NRF technique

In NRF experiments using continuous bremsstrahlung the photon scattering cross sections off bound nuclear states at an excitation energy $E_x$ can be measured. The total cross section integrated over one resonance and the full solid angle

$$I_s = g\left(\pi\frac{\hbar c}{E_x}\right)^2 \frac{\Gamma_0 \Gamma_f}{\Gamma} \tag{1}$$

is determined absolutely [3,21] (for the odd-*A* nuclei an isotropic angular intensity distribution is assumed in the analysis). $\Gamma_0$, $\Gamma_f$, and $\Gamma$ are the decay widths of the excited state with spin $J$ to the ground state with spin $J_0$, to the final level,

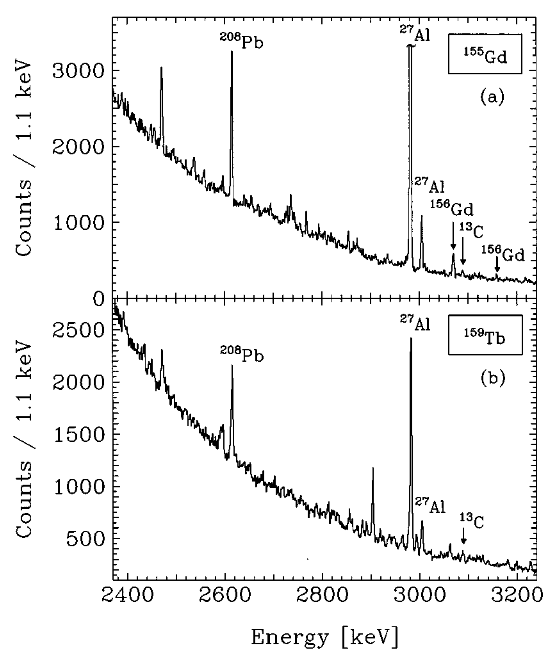


FIG. 1. Spectra of photons scattered off $^{155}$Gd and $^{159}$Tb measured at a bremsstrahlung endpoint energy of 4.1 MeV (see text). Calibration lines ($^{27}$Al), lines from background ($^{208}$Pb, $^{13}$C), and target impurities ($^{156}$Gd) are marked.

TABLE II. Results for the reaction $^{155}$Gd$(\gamma,\gamma')$: the excitation energies $E_x$, the integrated cross sections $I_s$, the products $g\Gamma_0$ of the spin factor $g$ and the ground-state transition widths $\Gamma_0$, the products $g\Gamma_0^{\rm red}$ of the spin factor $g$ and the reduced ground-state transition widths $\Gamma_0^{\rm red}$, and the reduced transition probabilities $B(M1)\uparrow$.

| $E_x$ [keV] | $I_s$ [eV b] | $g\Gamma_0$ [meV] | $g\Gamma_0^{\rm red}$ [meV/MeV$^3$] | $B(M1)\uparrow$ [a] [$\mu_N^2$] |
|---|---|---|---|---|
| 1675 | 7.3 ± 0.9 | 5.3 ± 0.6 | 1.128 ± 0.127 | 0.097 ± 0.011 |
| 1982 | 2.4 ± 0.6 | 2.5 ± 0.7 | 0.315 ± 0.083 | 0.027 ± 0.007 |
| 2017 | 6.3 ± 0.6 | 6.7 ± 0.7 | 0.819 ± 0.080 | 0.071 ± 0.007 |
| 2283 | 1.4 ± 0.3 | 1.9 ± 0.4 | 0.161 ± 0.034 | 0.014 ± 0.003 |
| 2329 | 1.5 ± 0.4 | 2.2 ± 0.6 | 0.170 ± 0.044 | 0.015 ± 0.004 |
| 2456 | 1.3 ± 0.3 | 4.1 ± 0.7 | 0.275 ± 0.050 | 0.024 ± 0.004 |
| 2558 | 2.1 ± 0.4 | 3.5 ± 0.6 | 0.209 ± 0.037 | 0.018 ± 0.003 |
| 2596 | 3.1 ± 0.4 | 5.5 ± 0.7 | 0.315 ± 0.040 | 0.027 ± 0.003 |
| 2645 | 1.3 ± 0.4 | 2.4 ± 0.8 | 0.129 ± 0.041 | 0.011 ± 0.004 |
| 2655 | 1.9 ± 0.4 | 11.3 ± 1.1 | 0.601 ± 0.058 | 0.052 ± 0.005 |
| 2689 | 1.3 ± 0.4 | 2.5 ± 0.8 | 0.130 ± 0.042 | 0.011 ± 0.004 |
| 2728 | 3.9 ± 0.5 | 7.5 ± 1.0 | 0.370 ± 0.051 | 0.032 ± 0.004 |
| 2743 | 2.6 ± 0.4 | 5.1 ± 0.8 | 0.249 ± 0.040 | 0.021 ± 0.003 |
| 2755 | 1.4 ± 0.3 | 7.4 ± 1.1 | 0.355 ± 0.053 | 0.031 ± 0.005 |
| 2768 | 2.9 ± 0.3 | 5.7 ± 0.7 | 0.270 ± 0.032 | 0.023 ± 0.003 |
| 2814 | 1.3 ± 0.4 | 2.8 ± 0.7 | 0.124 ± 0.033 | 0.011 ± 0.003 |
| 2819 | 1.3 ± 0.3 | 2.8 ± 0.6 | 0.124 ± 0.027 | 0.011 ± 0.002 |
| 2826 | 1.3 ± 0.4 | 2.6 ± 0.7 | 0.117 ± 0.032 | 0.010 ± 0.003 |
| 2854 | 3.6 ± 0.4 | 17.0 ± 1.2 | 0.732 ± 0.049 | 0.063 ± 0.004 |
| 2865 | 1.4 ± 0.3 | 6.0 ± 0.9 | 0.256 ± 0.037 | 0.022 ± 0.003 |
| 2872 | 2.6 ± 0.3 | 5.6 ± 0.7 | 0.235 ± 0.030 | 0.020 ± 0.003 |
| 3011 | 1.3 ± 0.3 | 3.2 ± 0.7 | 0.115 ± 0.025 | 0.010 ± 0.002 |
| 3123 | 1.5 ± 0.3 | 5.9 ± 1.1 | 0.194 ± 0.035 | 0.017 ± 0.003 |
| 3199 | 1.1 ± 0.3 | 3.0 ± 0.8 | 0.091 ± 0.023 | 0.008 ± 0.002 |
| 3305 | 1.8 ± 0.4 | 5.0 ± 1.0 | 0.140 ± 0.028 | 0.012 ± 0.002 |

[a]Assuming pure $M1$ transitions.

and the total level width, respectively. $g=(2J+1)/(2J_0+1)$ is the so-called spin factor. Since in NRF experiments on odd-$A$ nuclei, as discussed above, the spins $J$ of the photoexcited states cannot be determined, the spin factor $g$ is usually unknown. In the case of elastic scattering ($\Gamma_f=\Gamma_0$) the scattering cross section is proportional to $g\Gamma_0^2/\Gamma$. If the decay to excited states ($\Gamma_f/\Gamma_0$) can be observed or is known, the product of the spin factor and the ground-state decay width $g\Gamma_0$ can be determined. $g\Gamma_0$ is related to the reduced excitation probabilities $B(\Pi L,E_x)\uparrow=B(\Pi L;J_0\rightarrow J(E_x))$ ($\Pi=E$ or $M$) by

$$g\Gamma_0=8\pi\sum_{\Pi L=1}^{\infty}\frac{L+1}{L[(2L+1)!!]^2}\left(\frac{E_x}{\hbar c}\right)^{2L+1}B(\Pi L,E_x)\uparrow. \quad (2)$$

If the ground-state decay of the state at the energy $E_x$ is a pure dipole transition, the reduced dipole excitation probability

$$B(\Pi 1)\uparrow=gB(\Pi 1)\downarrow=\frac{9}{16\pi}\left(\frac{\hbar c}{E_x}\right)^3(g\Gamma_0) \quad (3)$$

TABLE III. Results for the reaction $^{155}$Gd$(\gamma,\gamma')$: excitation energies $E_x$ of photoexcited states with a decay to lower-lying states besides the ground state, spins and parities $J_f^\pi$ and $K$ quantum numbers $K_f$ of the fed excited levels, observed branching ratios $R_{\rm expt}$, branching ratios $R_{\rm theo}$ predicted by the Alaga rules, and spins $J$ and $K$ quantum numbers $K$ proposed for the photoexcited levels; see text.

| $E_x$ [keV] | $J_f^\pi$ | $K_f$ | $R_{\rm expt}$ | $R_{\rm theo}$ | $J$ | $K$ |
|---|---|---|---|---|---|---|
| 2456 | $5/2^-$ | 3/2 | 1.05 ± 0.38 | 1.50 | 3/2 | 1/2 |
| | | | | 0.67 | 3/2 | 3/2 |
| | | | | 0.97 | 5/2 | 3/2 |
| 2655 | $7/2^+$ | 3/2 | 2.58 ± 0.28 | - | 5/2 | 3/2;5/2 |
| 2755 | $5/2^-$ | 3/2 | 1.72 ± 0.51 | 1.50 | 3/2 | 1/2 |
| | | | | 0.97 | 5/2 | 3/2 |
| 2854 | $5/2^-$ | 3/2 | 0.49 ± 0.09 | 0.43 | 5/2 | 5/2 |
| | $7/2^+$ | 3/2 | 0.86 ± 0.11 | - | 5/2 | 5/2 |
| 2865 | $5/2^-$ | 3/2 | 1.14 ± 0.33 | 1.50 | 3/2 | 1/2 |
| | | | | 0.67 | 3/2 | 3/2 |
| | | | | 0.97 | 5/2 | 3/2 |
| 3123 | $5/2^-$ | 3/2 | 0.63 ± 0.26 | 0.67 | 3/2 | 3/2 |
| | | | | 0.97 | 5/2 | 3/2 |
| | | | | 0.43 | 5/2 | 5/2 |

can be extracted from the data. Then the following numerical relations hold:

$$B(E1)\uparrow=\frac{2.866}{3}\frac{g\Gamma_0}{E_x^3}[10^{-3}\ e^2\ {\rm fm}^2], \quad (4)$$

$$B(M1)\uparrow=\frac{0.2598}{3}\frac{g\Gamma_0}{E_x^3}[\mu_N^2], \quad (5)$$

for electric or magnetic dipole excitations, respectively, where the excitation energies $E_x$ should be taken in [MeV] and the ground-state transition widths $\Gamma_0$ in [meV].

In NRF experiments on odd-$A$ nuclei, as discussed above, the spins $J$ and parities of the photoexcited levels cannot be determined. The spin factor $g$ is not known. Therefore, we introduce for the following discussions the quantity $g\Gamma_0^{\rm red}$, the product of the spin factor $g$ and the reduced ground-state transition width $\Gamma_0^{\rm red}$,

$$g\Gamma_0^{\rm red}=g\frac{\Gamma_0}{E_x^3}. \quad (6)$$

This product can be directly measured and is proportional to the corresponding reduced transition probablities $B(\Pi L)\uparrow$ [see Eqs. (4) and (5)].

In some cases information on the spins $J$ of the photoexcited states can be extracted from the measured decay branching ratio $R_{\rm expt}$ to lower-lying states. This quantity $R_{\rm expt}$ is defined as

$$R_{\rm expt}=\frac{B(\Pi L;J\rightarrow J_f)}{B(\Pi L;J\rightarrow J_0)}=\frac{\Gamma_f}{\Gamma_0}\frac{E^3_{\gamma J_0}}{E^3_{\gamma J_f}}. \quad (7)$$

TABLE IV. Results for the reaction $^{159}$Tb$(\gamma,\gamma')$: the excitation energies $E_x$, the integrated cross sections $I_s$, the products $g\Gamma_0$ of the spin factor $g$ and the ground-state transition widths $\Gamma_0$, the products $g\Gamma_0^{\rm red}$ of the spin factor $g$ and the reduced ground-state transition widths $\Gamma_0^{\rm red}$, and the reduced transition probabilities $B(M1)\uparrow$.

| $E_x$ [keV] | $I_s$ [eV b] | $g\Gamma_0$ [meV] | $g\Gamma_0^{\rm red}$ [meV/MeV$^3$] | $B(M1)\uparrow$ [a] [$\mu_N^2$] |
|---|---|---|---|---|
| 1254 | 35.0 ± 9.0 | 24.0 ± 5.0 | 12.170 ± 2.536 | 1.100 ± 0.200 |
| 1317 | 12.0 ± 3.0 | 9.8 ± 1.9 | 4.290 ± 0.832 | 0.370 ± 0.070 |
| 1637 | 7.6 ± 1.8 | 8.5 ± 1.6 | 1.938 ± 0.365 | 0.170 ± 0.030 |
| 1709 | 7.0 ± 2.0 | 5.2 ± 1.8 | 1.042 ± 0.361 | 0.090 ± 0.030 |
| 1896 | 2.2 ± 1.1 | 2.0 ± 1.1 | 0.293 ± 0.161 | 0.026 ± 0.013 |
| 2020 | 5.7 ± 1.2 | 6.1 ± 1.3 | 0.740 ± 0.158 | 0.063 ± 0.014 |
| 2089 | 3.8 ± 1.1 | 4.3 ± 1.2 | 0.472 ± 0.132 | 0.041 ± 0.011 |
| 2116 | 14.0 ± 2.0 | 21.0 ± 3.0 | 2.217 ± 0.317 | 0.190 ± 0.020 |
| 2183 | 2.4 ± 0.4 | 3.0 ± 0.5 | 0.288 ± 0.048 | 0.025 ± 0.004 |
| 2192 | 4.0 ± 2.0 | 6.0 ± 3.0 | 0.570 ± 0.285 | 0.050 ± 0.020 |
| 2219 | 1.7 ± 0.1 | 2.2 ± 0.1 | 0.198 ± 0.009 | 0.017 ± 0.001 |
| 2223 | 2.6 ± 0.7 | 3.4 ± 0.8 | 0.309 ± 0.073 | 0.026 ± 0.007 |
| 2257 | 6.0 ± 2.0 | 8.0 ± 3.0 | 0.696 ± 0.261 | 0.060 ± 0.020 |
| 2270 | 1.4 ± 0.6 | 1.9 ± 0.8 | 0.162 ± 0.068 | 0.014 ± 0.006 |
| 2319 | 9.0 ± 1.2 | 22.0 ± 2.0 | 1.764 ± 0.160 | 0.153 ± 0.014 |
| 2339 | 4.8 ± 1.2 | 11.5 ± 1.9 | 0.899 ± 0.148 | 0.078 ± 0.013 |
| 2359 | 6.6 ± 0.5 | 9.6 ± 0.7 | 0.731 ± 0.053 | 0.063 ± 0.004 |
| 2372 | 2.8 ± 0.4 | 4.1 ± 0.6 | 0.307 ± 0.045 | 0.026 ± 0.004 |
| 2434 | 2.9 ± 1.1 | 4.5 ± 1.7 | 0.312 ± 0.118 | 0.027 ± 0.010 |
| 2445 | 2.2 ± 0.3 | 3.4 ± 0.4 | 0.233 ± 0.027 | 0.020 ± 0.003 |
| 2590 | 3.3 ± 0.4 | 5.8 ± 0.8 | 0.334 ± 0.046 | 0.029 ± 0.004 |
| 2595 | 4.6 ± 1.4 | 8.0 ± 2.0 | 0.458 ± 0.114 | 0.040 ± 0.012 |
| 2638 | 2.0 ± 0.6 | 7.0 ± 2.0 | 0.381 ± 0.109 | 0.035 ± 0.011 |
| 2651 | 2.6 ± 0.5 | 9.0 ± 2.0 | 0.483 ± 0.107 | 0.044 ± 0.010 |
| 2677 | 2.8 ± 0.3 | 5.2 ± 0.5 | 0.271 ± 0.026 | 0.024 ± 0.002 |
| 2701 | 2.7 ± 0.5 | 5.2 ± 0.9 | 0.264 ± 0.046 | 0.023 ± 0.004 |
| 2718 | 1.9 ± 1.3 | 4.0 ± 2.0 | 0.199 ± 0.100 | 0.016 ± 0.010 |
| 2755 | 1.8 ± 1.6 | 4.0 ± 3.0 | 0.191 ± 0.143 | 0.015 ± 0.013 |
| 2787 | 2.7 ± 0.7 | 5.4 ± 1.4 | 0.249 ± 0.065 | 0.022 ± 0.005 |
| 2831 | 2.7 ± 0.3 | 5.6 ± 0.7 | 0.247 ± 0.031 | 0.021 ± 0.003 |
| 2855 | 4.5 ± 1.2 | 9.0 ± 2.0 | 0.387 ± 0.086 | 0.035 ± 0.009 |
| 2870 | 2.1 ± 0.4 | 11.0 ± 3.0 | 0.465 ± 0.127 | 0.040 ± 0.011 |
| 2881 | 3.3 ± 0.6 | 18.0 ± 4.0 | 0.753 ± 0.167 | 0.064 ± 0.013 |
| 2890 | 4.3 ± 0.4 | 9.3 ± 0.8 | 0.385 ± 0.033 | 0.033 ± 0.003 |
| 2903 | 17.3 ± 0.8 | 37.9 ± 1.7 | 1.549 ± 0.069 | 0.134 ± 0.006 |
| 2918 | 3.7 ± 0.8 | 19.0 ± 3.0 | 0.765 ± 0.121 | 0.065 ± 0.012 |
| 2924 | 2.2 ± 0.9 | 5.0 ± 2.0 | 0.200 ± 0.080 | 0.017 ± 0.007 |
| 2938 | 2.6 ± 0.6 | 5.8 ± 1.2 | 0.229 ± 0.047 | 0.020 ± 0.004 |
| 2947 | 3.2 ± 0.9 | 7.0 ± 2.0 | 0.274 ± 0.078 | 0.025 ± 0.007 |
| 2963 | 3.8 ± 0.4 | 8.6 ± 0.9 | 0.331 ± 0.035 | 0.029 ± 0.003 |
| 2993 | 4.5 ± 0.8 | 10.5 ± 1.8 | 0.392 ± 0.067 | 0.034 ± 0.006 |
| 3018 | 2.2 ± 0.5 | 5.1 ± 1.1 | 0.186 ± 0.040 | 0.016 ± 0.004 |
| 3062 | 5.4 ± 1.2 | 13.0 ± 3.0 | 0.453 ± 0.104 | 0.039 ± 0.009 |
| 3079 | 2.4 ± 0.5 | 13.0 ± 4.0 | 0.445 ± 0.137 | 0.037 ± 0.012 |
| 3102 | 2.7 ± 1.3 | 7.0 ± 3.0 | 0.235 ± 0.101 | 0.020 ± 0.010 |
| 3117 | 2.7 ± 1.8 | 7.0 ± 4.0 | 0.231 ± 0.132 | 0.019 ± 0.013 |
| 3129 | 3.1 ± 0.1 | 7.9 ± 0.3 | 0.258 ± 0.010 | 0.022 ± 0.001 |
| 3159 | 1.4 ± 0.6 | 3.5 ± 1.7 | 0.111 ± 0.054 | 0.010 ± 0.005 |
| 3180 | 3.2 ± 0.6 | 8.5 ± 1.6 | 0.264 ± 0.050 | 0.023 ± 0.004 |
| 3198 | 2.3 ± 0.8 | 12.0 ± 4.0 | 0.367 ± 0.122 | 0.031 ± 0.009 |
| 3227 | 3.9 ± 0.1 | 10.5 ± 0.4 | 0.312 ± 0.012 | 0.027 ± 0.001 |
| 3368 | 3.2 ± 0.7 | 10.0 ± 2.0 | 0.262 ± 0.052 | 0.022 ± 0.005 |

[a] Assuming pure $M1$ transitions.

For deformed nuclei, in the rotational limit, the theoretical branching ratio $R_{\rm theo}$ is given by

$$R_{\rm theo}=\left|\frac{\sqrt{2J_f+1}\langle J_f,K_f,L,K-K_f|J,K\rangle}{\sqrt{2J_0+1}\langle J_0,K_0,L,K-K_0|J,K\rangle}\right|^2 \qquad (8)$$

and allows the $K$-quantum number $K$ of the excited state to be determined assuming the validity of these so-called Alaga rules [22].

## III. RESULTS

Figure 1 shows the experimental spectra of photons scattered off $^{155}$Gd and $^{159}$Tb. In both cases the spectra taken by the three individual detectors are summed up. The peaks marked by $^{27}$Al correspond to transitions in $^{27}$Al. Disks of this isotope sandwich the target and serve for the photon flux calibration [23]. The non-negligible effect of small impurities in the enriched $^{155}$Gd target material is demonstrated by the presence of the peaks labeled by $^{156}$Gd. This problem does not exist in the case of the chemically pure, naturally monoisotopic $^{159}$Tb sample. Already a short inspection of these spectra shows the pronounced fragmentation of the total strength into a large number of peaks.

TABLE V. Results for the reaction $^{159}$Tb$(\gamma,\gamma')$: excitation energies $E_x$ of photoexcited states with a decay to lower-lying states besides the ground state, spins and parities $J_f^\pi$ and $K$ quantum numbers $K_f$ of the fed excited levels, observed branching ratios $R_{\rm expt}$, branching ratios $R_{\rm theo}$ predicted by the Alaga rules, and spins $J$ and $K$ quantum numbers $K$ proposed for the photoexcited levels; see text.

| $E_x$ [keV] | $J_f^\pi$ | $K_f$ | $R_{\rm expt}$ | $R_{\rm theo}$ | $J$ | $K$ |
|---|---|---|---|---|---|---|
| 1254 | $5/2^+$ | 3/2 | 0.72 ± 0.08 | 0.67 | 3/2 | 3/2 |
| 1317 | $5/2^+$ | 3/2 | 0.86 ± 0.14 | 0.67 | 3/2 | 3/2 |
| | | | | 0.97 | 5/2 | 3/2 |
| 1637 | $5/2^+$ | 3/2 | 0.72 ± 0.15 | 0.67 | 3/2 | 3/2 |
| 2116 | $5/2^+$ | 3/2 | 0.37 ± 0.05 | 0.43 | 5/2 | 5/2 |
| 2319 | $5/2^+$ | 3/2 | 0.81 ± 0.07 | 0.67 | 3/2 | 3/2 |
| 2339 | $5/2^+$ | 3/2 | 0.64 ± 0.11 | 0.67 | 3/2 | 3/2 |
| 2870 | $5/2^+$ | 3/2 | 1.50 ± 0.30 | 1.50 | 3/2 | 1/2 |
| 2881 | $5/2^+$ | 3/2 | 0.76 ± 0.16 | 0.67 | 3/2 | 3/2 |
| | | | | 0.97 | 5/2 | 3/2 |
| 2918 | $5/2^+$ | 3/2 | 0.70 ± 0.14 | 0.67 | 3/2 | 3/2 |
| | | | | 0.97 | 5/2 | 3/2 |
| 3198 | $5/2^+$ | 3/2 | 0.80 ± 0.20 | 0.67 | 3/2 | 3/2 |
| | | | | 0.97 | 5/2 | 3/2 |

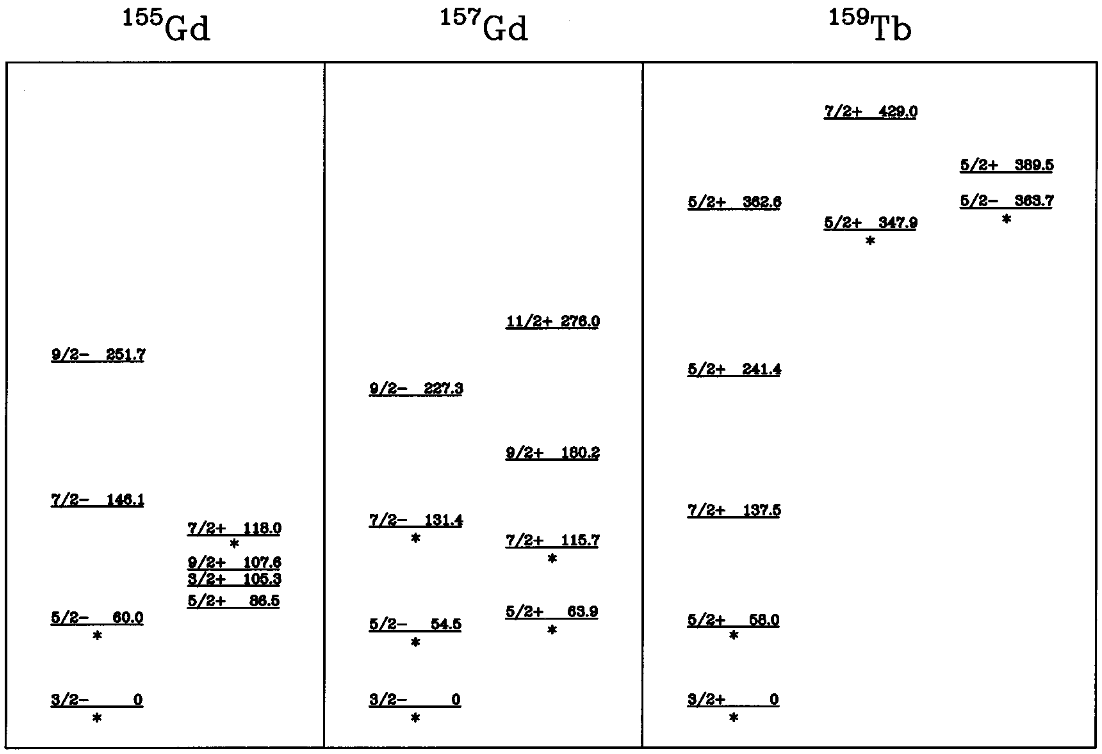


FIG. 2. Comparison of low-lying collective bands in the odd nuclei $^{155,157}$Gd and $^{159}$Tb. Spins, parities, and excitation energies are given. States, which are fed by transitions from levels excited in the present photon scattering experiments, are marked by asterisks.

Table II summarizes the results for $^{155}$Gd$(\gamma,\gamma')$ in numerical form. The quoted quantities are the excitation energies $E_x$ (with an error of $\leqslant$ 1 keV), the integrated cross sections $I_s$, the products $g\Gamma_0$ of the spin factor $g$ and the ground-state transition widths $\Gamma_0$, the products $g\Gamma_0^{\rm red}$ of the spin factor $g$ and the reduced ground-state transition widths $\Gamma_0^{\rm red}$, and the reduced transition probabilities $B(M1)\uparrow$ assuming $M1$ excitations.

In some cases a decay of the photoexcited level to a low-lying excited state, besides the ground state, was observed. For these levels the observed branching ratios $R_{\rm expt}$, the spins and parities $J_f^\pi$, and the $K$-quantum numbers $K_f$ of the final states populated besides the ground state are summarized in Table III. Furthermore, the spins $J$ and quantum numbers $K$ of the photoexcited levels are quoted as suggested by the comparison of the observed decay branchings $R_{\rm expt}$ and the branchings $R_{\rm theo}$ predicted by the Alaga rules. Tables IV and V show the same quantities observed in the reaction $^{159}$Tb$(\gamma,\gamma')$. The numerical results for the corresponding $(\gamma,\gamma')$ reactions on $^{157}$Gd and $^{161,163}$Dy can be found in the tables presented in our previous publications [11,14].

In Fig. 2 the low-lying collective bands in $^{155,157}$Gd and $^{159}$Tb below 500 keV are compared. The levels, besides the ground states, which are fed by the decay of some of the levels photoexcited in the present NRF experiments are marked by asterisks. As already discussed in Ref. [14] in the case of $^{161,163}$Dy and $^{157}$Gd the different behavior of the dipole strength fragmentation in the various odd isotopes cannot simply be explained by a different number of possibilities for decays to various excited states in the low-lying collective bands.

## IV. DISCUSSION

In the following we want to discuss the observed different fragmentation of the low-lying dipole strength in the odd isotopes of the Dy and Gd isotopic chains. Figure 3 summarizes the experimental data for $^{160,161,162,163,164}$Dy in the energy range of the scissors mode (see [14] and references therein). Plotted is the product $g\Gamma_0^{\rm red}$ for the odd nuclei and $\Gamma_0^{\rm red}$ for the even-even isotopes (for these nuclei the spin factor $g$ amounts to $g=3$). In the case of the even-even isotopes only $\Delta K=1$ excitations are shown. The $M1$ character of the stronger excitations in $^{162,164}$Dy was established by NRF polarization measurements [13,14]. The insets give the summed values of $g\Gamma_0^{\rm red}$ (summed in the energy range 2–4 MeV), which can directly be converted into the total $B(M1)\uparrow$ strengths using the numerical relation (5). The total strength in the even-even Dy isotopes increases with the mass number $A$. It should be noted that the extremely high total $M1$ strength in $^{164}$Dy contains a considerable spin contribution as observed in proton scattering experiments [25]. The $B(M1)\uparrow$ strength summed up over the proper energy range of the scissors mode (2.7–3.7 MeV) [24] is rather constant and exhausts the $M1$ scissors mode sum rule, as derived recently by Lo Iudice and Richter [26]. For the odd isotopes $^{161,163}$Dy the concentration of the dipole strength and its energetic position fit into the systematics of the even-

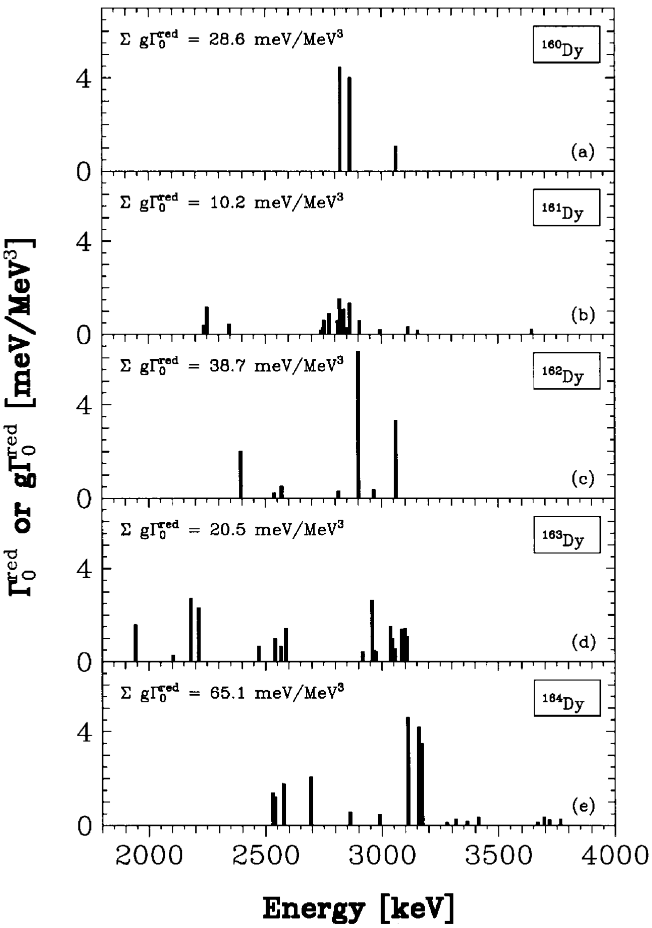

FIG. 3. Dipole strength distributions in the isotopes $^{160,161,162,163,164}$Dy [parts (a)–(e)]. For the even-even isotopes the reduced ground-state widths $\Gamma_0^{\mathrm{red}}$ of $\Delta K=1$ transitions are plotted. In the case of the odd nuclei $^{161,163}$Dy, because of the unknown spins $J$ of the excited states, the products of the reduced ground-state decay widths $\Gamma_0^{\mathrm{red}}$ and the spin factor $g=(2J+1)/(2J_0+1)$ are plotted; see text.

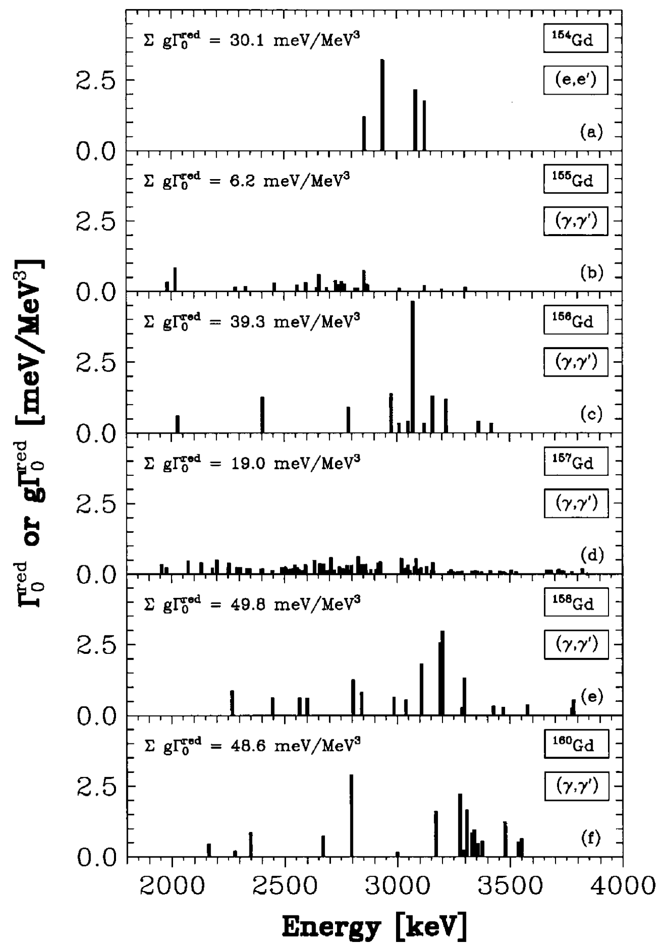

FIG. 4. Dipole strength distributions in the isotopes $^{154,155,156,157,158,160}$Gd [parts (a)–(f)]. For the even-even isotopes the reduced ground-state widths $\Gamma_0^{\mathrm{red}}$ of $\Delta K=1$ transitions are plotted. In the case of the odd nuclei $^{155,157}$Gd, because of the unknown spins $J$ of the excited states, the products of the reduced ground-state decay widths $\Gamma_0^{\mathrm{red}}$ and the spin factor $g=(2J+1)/(2J_0+1)$ are plotted; see text.

even isotopes. However, the experimentally detected total strength is about a factor of 3 lower than in their even-even neighbors.

For $^{163}$Dy explicit calculations are available. The IBFM calculations by Bauske *et al.* [11] support the interpretation as scissors mode excitations, give the right order of the total strength, and explain the observed decay branchings (see [14]). However, it should be emphasized that the calculated $B(M1)$ values depend on the square of the difference between the neutron and proton boson $g$ factors $(g_\nu - g_\pi)^2$. In the calculations of Bauske *et al.* a value of 0.36 was used as suggested by Wolf *et al.* [27]. On the other hand, one has to note that when taking the same average boson $g$ factors in the neighboring even-even nuclei the sum rule predictions given for total $B(M1)\uparrow$ strengths within the framework of the IBA-2 model [28] are about a factor of 2–3 lower than the experimentally observed strengths in these nuclei. Quite recently Soloviev *et al.* [8] reported on QPNM calculations of low-lying $M1$ strength in $^{163}$Dy. As pointed out in this paper in these calculations for the odd isotope $^{163}$Dy there is no free parameter since all constants were fixed during the construction of the phonon basis in the neighboring even nucleus $^{162}$Dy where their calculations are in a fair agreement with the experimental data [12,13]. In their calculations Soloviev *et al.* found in $^{163}$Dy a concentration of $M1$ strength near 2.5 and 3.0 MeV in agreement with the experiments [11]. However, the total summed strength below 3.2 MeV of $\Sigma B(M1)\uparrow = 3.2\mu_N^2$ overestimates the experimentally observed strength roughly by a factor of 2.

In Fig. 4 the available experimental data for the stable Gd isotopes $^{154,155,156,157,158,160}$Gd are summarized and compared. Here also the product $g\Gamma_0^{\mathrm{red}}$ for the odd nuclei and $\Gamma_0^{\mathrm{red}}$ for the even-even isotopes is plotted. In the case of the even-even isotopes only $\Delta K=1$ excitations are shown. For the strong excitations in $^{154,156,158}$Gd around 3 MeV the $M1$ character is known from electron scattering form factor measurements [1,16,18,29]. The $M1$ character of the stronger excitations in $^{160}$Gd was established by NRF polarization measurements [13,19]. The insets at the upper left of each panel give the summed values of $g\Gamma_0^{\mathrm{red}}$ (summed in the energy range 2–4 MeV). The total strength in the even-even Gd isotopes increases with the mass number $A$. This is in agreement with the expected increase of the total $B(M1)$

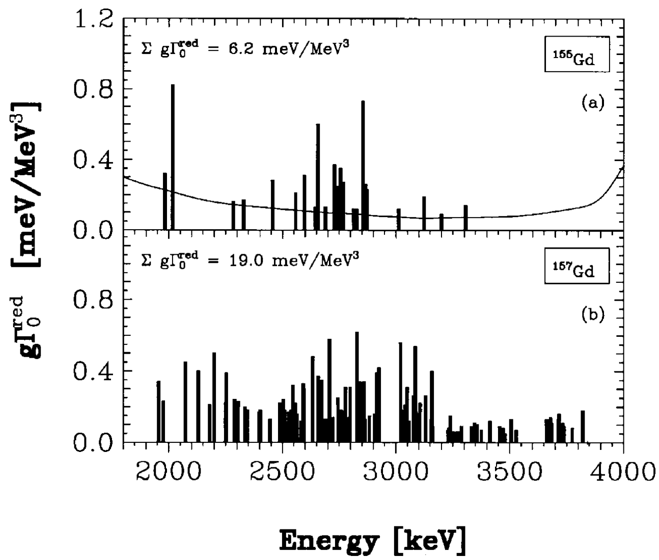


FIG. 5. Comparison of the observed dipole strength distributions in $^{155}$Gd and $^{157}$Gd. Plotted are the products $g\Gamma_0^{red}$ of the spin factor $g$ and the reduced ground-state transition width $\Gamma_0^{red}$; see text. The solid line in part (a) indicates the sensitivity limit in the present NRF experiments.

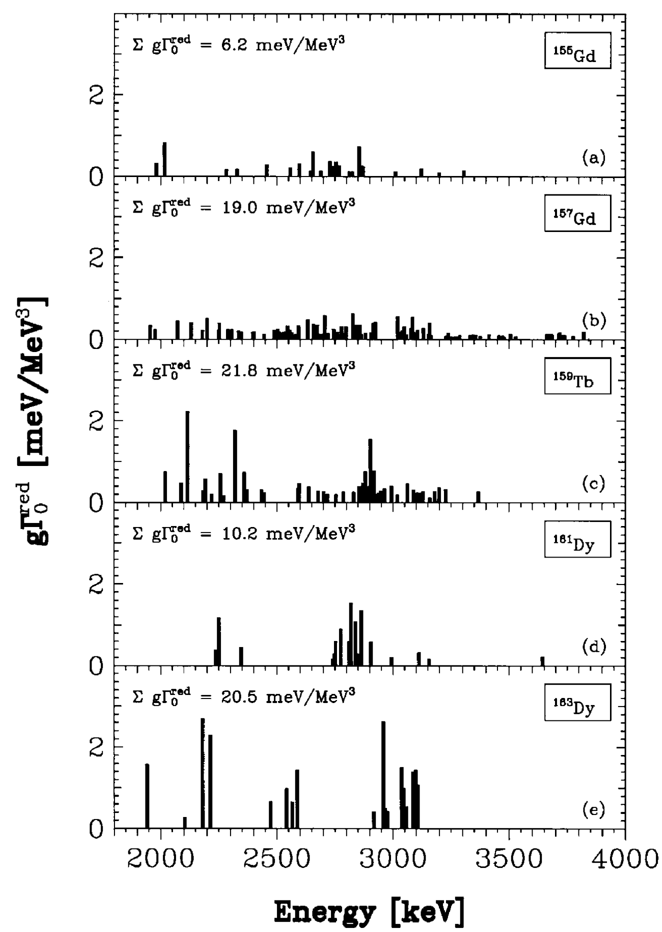


FIG. 6. Comparison of the observed dipole strength distributions in the odd rare earth nuclei $^{155,157}$Gd, $^{159}$Tb, and $^{161,163}$Dy [parts (a)–(e)]. Plotted are the products of the spin factor $g$ and the reduced ground-state transition width $\Gamma_0^{red}$ as a function of the excitation energy; see text.

strength proportional to the square of the deformation parameter $\delta$ (so-called ''$\delta^2$ *law*'') (see [30–32]). Furthermore, the detected $M1$ strengths exhaust the $M1$ sum rule prediction by Lo Iuduce and Richter [26].

The striking difference of the dipole strength distributions in the Gd isotopes $^{155,157}$Gd as compared to the odd Dy nuclei is the obviously very strong fragmentation. In addition the total strengths are reduced, in particular in $^{155}$Gd. In view of the small transition widths of the individual excitations weak $E1$ excitations cannot be excluded. Considering the increased sensitivity of the present NRF experiments even $E2$ excitations cannot be excluded. Typical noncollective $E2$ transitions may be of the order of 1 Weisskopf unit [$B(E2)_W = 0.06A^{4/3}\ e^2\ \mathrm{fm}^4 \approx 0.005\ e^2\ \mathrm{b}^2$ in Gd and Tb]. The associated decay width is

$$\Gamma_{E2}^{W} = 4.8\times 10^{-5} A^{4/3} (E_\gamma/\mathrm{MeV})^5\ \ \mathrm{meV}, \tag{9}$$

which amounts to $\Gamma_{E2}^{W} > 1$ meV for states in Gd and Tb at excitation energies of above 2 MeV. This is the same order of magnitude as the values of the level widths observed for the states which we interpret as dipole excitations. Therefore, the really detected total $M1$ strengths might be still lower than the numbers given in the insets of Figs. 3, 4, and 6.

The reduced observed dipole strength in $^{155}$Gd cannot be explained by a lack of sensitivity in the present NRF experiments. This is demonstrated in Fig. 5. In this figure the dipole strength distributions in $^{155}$Gd (upper part) and $^{157}$Gd (lower part) are compared. The solid line in the upper part indicates the detection limit in the present measurements. Near 3.2 MeV it corresponds to a value of $B(M1)\uparrow_{\mathrm{limit}} \approx 0.006\mu_N^2$. As the depicted line shows, the sensitivity of the present NRF experiments is best near 3.2 MeV, in the energy range of the scissors mode. At lower energies ($E_\gamma \lesssim 2$ MeV) the increased background from nonresonantly scattered bremsstrahlung photons limits the sensitivity. At energies near the bremsstrahlung endpoint energies ($E_\gamma \approx$ 4 MeV) the lowered photon flux leads to a reduced sensitivity of the present NRF experiments.

The detection limit in the $^{157}$Gd measurement was even somewhat better. However, with the shown detection limits of the $^{155}$Gd experiment only 5 very weak transitions of the about 90 observed excitations in $^{157}$Gd would have been missed. Therefore, the observed decrease of the total dipole strength in $^{155}$Gd has to be considered as a real physical effect and not as an artifact of the measurements. The lacking strength or extreme fragmentation in the odd Gd isotopes as compared to $^{161,163}$Dy is unexplained. The only calculation for an odd Gd isotope ($^{157}$Gd) has been performed quite recently by Devi and Kota [33] in the framework of the interacting boson-fermion model including $s$, $d$, and $g$ bosons and the proton-neutron degree of freedom. However, their results do not reproduce the difference in strength fragmentation for the odd Dy and Gd isotopes.

Empirically it seems that the fragmentation increases when going from $^{163}$Dy to the lighter Gd isotopes. This can be seen in Fig. 6 where the dipole strength distributions for $^{155,157}$Gd, $^{159}$Tb, and $^{161,163}$Dy are plotted. For $^{159}$Tb the dipole strength distribution shows an intermediate fragmentation. When discussing the observed total strength, given as $\Sigma g\Gamma_0^{\mathrm{red}}$, one has to keep in mind that these values also may include possible $E1$ or even $E2$ excitations which cannot be distinguished in the present NRF experiments.

The principal questions are, where is the missing strength of the scissors mode in the odd nuclei and what is the reason for the different fragmentation in various nuclei? The different strength fragmentation is unexplained up to now. There is an urgent need for more theoretical work. Concerning the strength it would be a surprise if the total strength of the scissors mode in odd nuclei really would be reduced as compared to the neighboring even-even nuclei. In other cases of the weak coupling of an unpaired nucleon to a rather collective core excitation the total strength is rather conserved; e.g., the coupling of an unpaired neutron to two-phonon excitations ($2^+ \otimes 3^-$) in spherical $N=82$ isotopes [34] leads to a two-phonon⊗particle multiplet of comparable total strength [34,35]. To search for the missing strength two directions might be appropriate and promising. If really the fragmentation is so large that the individual excitations are too weak to be detected by the present most sensitive NRF experiments, a statistical analysis as proposed by the Darmstadt group [36] may give some estimate of the missing strength hidden unresolved in the background of the NRF spectra. Another speculative explanation would be a not expected shift of the $M1$ strength to energies above 4 MeV which are not accessible in the present NRF experiments. A very recent NRF study of the isotope $^{167}$Er performed at the Darmstadt *S*-DALINAC facility in an extended excitation energy range up to 4.3 MeV revealed considerable dipole strength above 4 MeV [37]. Assuming all strength to be of $M1$ character a total strength of $\approx (3\pm 1)\mu_N^2$ was detected ($E_\gamma$ = 2.5–4.3 MeV) which would nicely fit into the systematics of the neighboring even-even Er isotopes $^{166,168,170}$Er [38]. The portion of strength in the energy range 4.0–4.3 MeV detected in these experiments on $^{167}$Er was about $1\mu_N^2$ (assuming $M1$ excitations).

It should be emphasized, once again, that in all NRF experiments on odd-*A* nuclei *no* parity assignments are possible. Therefore, contributions from electric transitions cannot be excluded and substantially complicate the discussion. In particular at higher excitation energies ($E \geqslant 4$ MeV) more and more $E1$ strength is expected from the tail of the electric giant dipole resonance (GDR). This fact dramatically increases the difficulty of the interpretation of NRF experiments to study the $M1$ strength distribution of the scissors mode in odd nuclei. In conclusion, there is a need for further experiments, using not only photon scattering, but other nuclear probes as well, and for more theoretical work to really solve the problems of fragmentation and missing strength of the scissors mode in odd-*A* nuclei.

**ACKNOWLEDGMENTS**

We wish to thank A. Richter, V.G. Soloviev, and P. Van Isacker for stimulating and enlightening discussions. The support by the Deutsche Forschungsgemeinschaft under Contracts Nos. Br 799/6, Kn 154/21, and Kn 154/30 is gratefully acknowledged.

[1] D. Bohle, A. Richter, W. Steffen, A.E.L. Dieperink, N. Lo Iudice, F. Palumbo, and O. Scholten, Phys. Lett. **137B**, 27 (1984).
[2] A. Richter, Prog. Part. Nucl. Phys. **34**, 261 (1995).
[3] U. Kneissl, H.H. Pitz, and A. Zilges, Prog. Part. Nucl. Phys. **37**, 349 (1996).
[4] P. Van Isacker and A. Frank, Phys. Lett. B **225**, 1 (1989).
[5] A. Frank, J.M. Arias, and P. Van Isacker, Nucl. Phys. **A531**, 125 (1991).
[6] A.A. Raduta and N. Lo Iudice, Z. Phys. A **334**, 403 (1989).
[7] A.A. Raduta and D.S. Delion, Nucl. Phys. **A513**, 11 (1990).
[8] V.G. Soloviev, A.V. Sushkov, and N.Yu. Shirikova, Phys. Rev. C **53**, 1022 (1996).
[9] W. Geiger, Zs. Németh, I. Bauske, P. von Brentano, R.D. Heil, R.-D. Herzberg, U. Kneissl, J. Margraf, H. Maser, N. Pietralla, H.H. Pitz, C. Wesselborg, and A. Zilges, Nucl. Phys. **A580**, 263 (1994).
[10] N. Huxel, W. Ahner, H. Diesener, P. von Neumann-Cosel, C. Rangacharyulu, A. Richter, C. Spieler, W. Ziegler, C. De Coster, and K. Heyde, Nucl. Phys. **A539**, 478 (1992).
[11] I. Bauske, J.M. Arias, P. von Brentano, A. Frank, H. Friedrichs, R.D. Heil, R.-D. Herzberg, F. Hoyler, P. Van Isacker, U. Kneissl, J. Margraf, H.H. Pitz, C. Wesselborg, and A. Zilges, Phys. Rev. Lett. **71**, 975 (1993).
[12] 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. B **207**, 22 (1988).
[13] H. Friedrichs, B. Schlitt, J. Margraf, S. Lindenstruth, C. Wesselborg, R.D. Heil, H.H. Pitz, U. Kneissl, P. von Brentano, R.-D. Herzberg, A. Zilges, D. Häger, G. Müller, and M. Schumacher, Phys. Rev. C **45**, R892 (1992).
[14] J. Margraf, T. Eckert, M. Rittner, I. Bauske, O. Beck, U. Kneissl, H. Maser, H.H. Pitz, A. Schiller, P. von Brentano, R. Fischer, R.-D. Herzberg, N. Pietralla, A. Zilges, and H. Friedrichs, Phys. Rev. C **52**, 2429 (1995).
[15] U.E.P. Berg, C. Bläsing, J. Drexler, R.D. Heil, U. Kneissl, W. Naatz, R. Ratzek, S. Schennach, R. Stock, T. Weber, B. Fischer, H. Hollick, and D. Kollewe, Phys. Lett. **149B**, 59 (1984).
[16] D. Bohle, A. Richter, U.E.P. Berg, J. Drexler, R.D. Heil, U. Kneissl, H. Metzger, R. Stock, B. Fischer, H. Hollick, and D. Kollewe, Nucl. Phys. **A458**, 205 (1986).
[17] H.H. Pitz, U.E.P. Berg, R.D. Heil, U. Kneissl, R. Stock, C. Wesselborg, and P. von Brentano, Nucl. Phys. **A492**, 411 (1989).
[18] U. Hartmann, D. Bohle, F. Humbert, and A. Richter, Nucl. Phys. **A499**, 93 (1989).
[19] H. Friedrichs, D. Häger, P. von Brentano, R.D. Heil, R.-D. Herzberg, U. Kneissl, J. Margraf, G. Müller, H.H. Pitz, B. Schlitt, M. Schumacher, C. Wesselborg, and A. Zilges, Nucl. Phys. **A567**, 266 (1994).
[20] U. Kneissl, Nucl. Phys. News **4**(2), 24 (1994).

[21] U.E.P. Berg and U. Kneissl, Annu. Rev. Nucl. Part. Sci. **37**, 33 (1987).

[22] G. Alaga, K. Alder, A. Bohr, and B.R. Mottelson, Dan. Mat. Fys. Medd. **29**(9), 1 (1955).

[23] N. Pietralla, I. Bauske, O. Beck, P. von Brentano, W. Geiger, R.-D. Herzberg, U. Kneissl, J. Margraf, H. Maser, H. H. Pitz, and A. Zilges, Phys. Rev. C **51**, 1021 (1995).

[24] N. Pietralla, P. von Brentano, R.-D. Herzberg, U. Kneissl, J. Margraf, H. Maser, H. H. Pitz, and A. Zilges, Phys. Rev. C **52**, R2317 (1995).

[25] D. Frekers, D. Bohle, A. Richter, R. Abegg, R.E. Azuma, A. Celler, C. Chan, T.E. Drake, K.P. Jackson, C.A. Miller, R. Schubank, J. Watson, and S. Yen, Phys. Lett. B **218**, 439 (1989).

[26] N. Lo Iudice and A. Richter, Phys. Lett. B **304**, 193 (1993).

[27] A. Wolf, D.D. Warner, and N. Benczer-Koller, Phys. Lett. **158B**, 7 (1985).

[28] B.R. Barrett and P. Halse, Phys. Lett. **155B**, 133 (1985).

[29] D. Bohle, G. Küchler, A. Richter, and W. Steffen, Phys. Lett. **148B**, 260 (1984).

[30] W. Ziegler, C. Rangacharyulu, A. Richter, and C. Spieler, Phys. Rev. Lett. **65**, 2515 (1990).

[31] J. Margraf, R.D. Heil, U. Maier, U. Kneissl, H.H. Pitz, H. Friedrichs, S. Lindenstruth, B. Schlitt, C. Wesselborg, P. von Brentano, R.-D. Herzberg, and A. Zilges, Phys. Rev. C **47**, 1474 (1993).

[32] W. Ziegler, N. Huxel, P. von Neumann-Cosel, C. Rangacharyulu, A. Richter, C. Spieler, C. De Coster, and K. Heyde, Nucl. Phys. **A564**, 366 (1993).

[33] Y.D. Devi and V.K.B. Kota, Nucl. Phys. **A600**, 20 (1996).

[34] A. Zilges, R.-D. Herzberg, P. von Brentano, F. Dönau, R.D. Heil, R.V. Jolos, U. Kneissl, J. Margraf, H.H. Pitz, and C. Wesselborg, Phys. Rev. Lett. **70**, 2880 (1993).

[35] R.-D. Herzberg, A. Zilges, A.M. Oros, P. von Brentano, U. Kneissl, J. Margraf, H.H. Pitz, and C. Wesselborg, Phys. Rev. C **51**, 1226 (1995).

[36] N. Huxel, P. von Brentano, J. Eberth, J. Enders, R.-D. Herzberg, P. von Neumann-Cosel, N. Nicolay, N. Pietralla, H. Prade, J. Reif, A. Richter, C. Schlegel, R. Schwengner, S. Skoda, H.G. Thomas, I. Wiedenhöver, G. Winter, and A. Zilges, Verhandl. DPG (VI) **31**, 976 (1996).

[37] C. Schlegel, P. von Neumann-Cosel, A. Richter, and P. Van Isacker, Phys. Lett. B **375**, 21 (1996).

[38] H. Maser, S. Lindenstruth, I. Bauske, O. Beck, P. von Brentano, T. Eckert, H. Friedrichs, R.D. Heil, R.-D. Herzberg, A. Jung, U. Kneissl, J. Margraf, N. Pietralla, H.H. Pitz, C. Wesselborg, and A. Zilges, Phys. Rev. C **53**, 2749 (1996).