Deformation dependence of low lying $M1$ strengths in even Nd isotopes

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Measurements of the linear polarization of resonantly scattered photons have been used for model independent parity assignments in nuclear resonance fluorescence experiments (NRF). Previous NRF investigations of the even-even Nd isotopes were completed by polarization measurements on the transitional nucleus ^{146}Nd. With these new parity assignments the systematics of low lying $M1$ strengths can be studied along the transition from spherical to deformed nuclear shapes. The total $M1$ strength in the excitation energy range of 2–4 MeV in the investigated even-even Nd isotopes increases proportionally to the square of the deformation parameter. These findings represent a reliable confirmation of the results recently reported for the Sm isotopes by the Darmstadt group. This deformation dependence can be explained by various recent theoretical approaches.

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The first observation of strong orbital $M1$ excitations in deformed even-even nuclei [1] stimulated a large number of both theoretical and experimental studies [2]. Numerous electron and photon scattering experiments established the systematics of this so-called scissors mode and investigated its fragmentation [2–4]. The transition from spherical to well deformed nuclear shapes was investigated in detail by nuclear resonance fluorescence (NRF) experiments on even-even nuclei of the Nd [5] and Sm isotopes [6], respectively. In the latter experiment the Darmstadt group observed that the total orbital $M1$ strength increases proportionally to the square of the deformation parameter δ [6]. This δ^2 dependence of orbital $M1$ strength originally was predicted by macroscopic models [7, 8]. The report on its observation in the Sm isotopes initiated another series of theoretical papers. As a result the deformation dependence of the orbital $M1$ strength is now described also in microscopic calculations [9–11]. Furthermore, the strong correlation and saturation of $E2$ and $M1$ strength observed for the deformed rare earth [12] and actinide [13] nuclei has been explained theoretically [14]. The systematics of $E2$ and $M1$ strengths and the quadrupole collectivity in the magnetic dipole strength have been discussed in a recent paper by Heyde *et al.* [15].

The even Nd nuclei (^{142,146,148,150}Nd) have two protons less than Sm isotopes and represent another favorable isotopic chain to study the transition from spherical to deformed nuclear shapes. These nuclei were already investigated in our previous NRF experiments [5]. In order to establish reliable parity assigments for all Nd isotopes our previous polarization experiments on the spherical nucleus ^{142}Nd ($N = 82$) and the deformed nucleus ^{150}Nd [16–18] were completed very recently by measurements on the transitional nucleus ^{146}Nd where rather concentrated dipole strength was observed [5]. These model-independent parity assignments for the $M1$ transitions in the Nd isotopes allow a crucial test of the deformation dependence of the total low lying $M1$ strength along the transition from spherical to deformed nuclei.

Of the various definitions of the deformation parameter found in literature [19] we prefer in this paper the deformation parameter β_2 which is directly connected to the experimentally accessible reduced transition probability $B(E2)$ and is proportional to the quadrupole moment Q_0:

$$\beta_2 = \frac{4\pi}{3}\frac{1}{ZR_0^2}\sqrt{\frac{B(E2)}{e^2}} = \frac{4\pi}{3}\frac{1}{ZR_0^2}\sqrt{\frac{5}{16\pi}}Q_0 \quad (1)$$

where Z represents the atomic number and R_0 corresponds to 1.2 fm.

The deformation parameter δ often used in previous papers on the same subject is related to β_2 by the expansion series [19]

$$\delta = \frac{3}{4}\sqrt{\frac{5}{\pi}}\beta_2 - \frac{15}{8\pi}\beta_2^2 + \cdots . \quad (2)$$

For nuclear deformations in the rare earth mass region both deformation parameters β_2 and δ differ by less than 30%. The deformation parameters β_2 and the $B(E2)$ values of the Nd isotopes as known from the literature [20] are summarized in Table I.

TABLE I. Deformation parameters β_2 for even Nd isotopes. Data are taken from the compilation of Ref. [20].

Isotope	β_2	$B(E2)\uparrow$ (e^2 b^2)
^{142}Nd	0.0926	0.270
^{146}Nd	0.1524	0.760
^{148}Nd	0.2036	1.380
^{150}Nd	0.2848	2.750

The experiments have been performed at the bremsstrahlung facility [21] installed at the Stuttgart Dynamitron Accelerator [E_0 = 4 MeV, $I \approx 0.8$ mA (CW)]. In the present NRF experiment on ^{146}Nd a sectored single crystal Ge Compton polarimeter [4, 22] has been used for the parity determinations. This device combines the advantages of a good energy resolution, an almost completely symmetrical response, and of a high coincidence efficiency. Its polarization sensitivity Q has been measured in $(p, p'\vec{\gamma})$-reaction studies and amounts to about 20% at 0.5 MeV and 10% at 4 MeV, respectively. Its performance is described in more detail in Refs. [4, 22].

The parity information is obtained from the measured azimuthal asymmetry ε :

$$\varepsilon = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} = QP_\gamma \qquad (3)$$

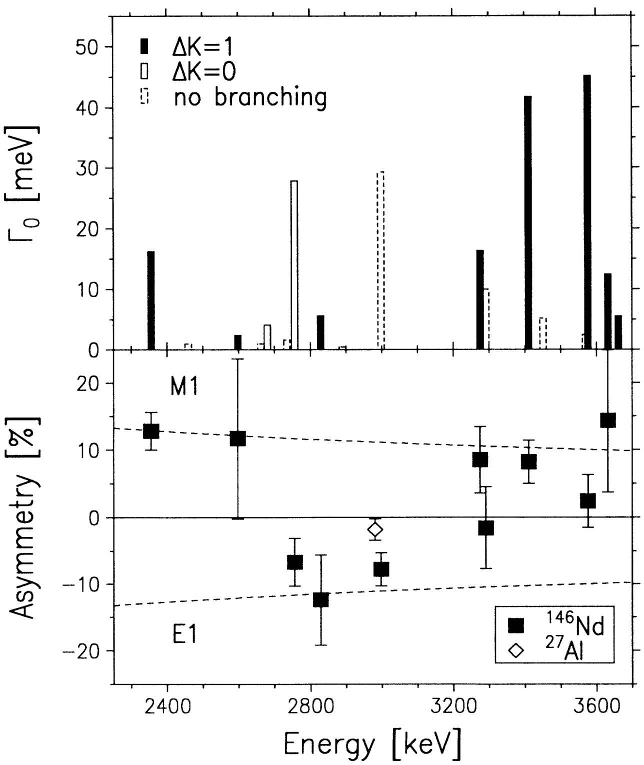

FIG. 1. Upper part: Ground-state transition widths Γ_0 of dipole excitations in ^{146}Nd. Full bars: spin 1 states with decay branchings $R_{\text{exp}} \le 1$ (K=1); dashed bars: spin 1 states with decay branchings $R_{\text{exp}} \ge 1$ (K=0); dotted bars: spin 1 states without any observed decay to excited states. Lower part: Azimuthal asymmetries ε. The dashed lines correspond to the asymmetries expected for pure $M1$ ($\varepsilon > 0$) and $E1$ ($\varepsilon < 0$) excitations, respectively.

TABLE II. Experimental data for ^{142}Nd taken from Refs. [5, 24]. The state at 4095 keV has been included since it has the same structure as the state at 3.97 MeV in the isotone ^{144}Sm (see Ref. [24]). The total $M1$ strength in ^{142}Nd then amounts to $\Sigma B(M1)\uparrow = (0.44 \pm 0.09)\mu_k^2$.

Energy (keV)	$B(M1)\uparrow$ (μ_k^2)	J^π
2583	0.02 $\pm$ 0.01	(1^+)
4095	0.42 $\pm$ 0.08	1^+

where $N_\perp$ and $N_\parallel$ represent the rates of Compton scattered events perpendicular and parallel to the NRF scattering plane defined by the directions of the photon beam and the scattered photons, respectively. At an NRF scattering angle of $\Theta = 90^o$ with respect to the bremsstrahlung beam axis the polarization P_γ amounts to -1 or $+1$ for pure $E1$ and $M1$ excitations, respectively (0-1-0 spin sequences). Therefore, obviously the sign of the asymmetry ε determines the parity.

Figure 1 shows the results obtained in the present ^{146}Nd$(\gamma, \vec{\gamma})$ experiments. In the upper part the ground-state transition widths Γ_0 of the observed dipole excitations are plotted. Different graphical illustrations correspond to different decay branchings to the ground state (0^+) and the first excited 2^+ state $R = B(1 \to 0^+)/B(1 \to 2^+)$ which, within the validity of the Alaga rules, give information on the K quantum number [23]. In the lower part of Fig. 1 the measured azimuthal asymmetries ε are plotted as a function of the transition energy. The dashed lines correspond to the asymmetries expected for pure $M1$ (positive ε) and $E1$ transitions (negative ε), respectively. Both $M1$ and $E1$ excitations occur. We note that two spin-1 states without observed decay branches to excited states obviously

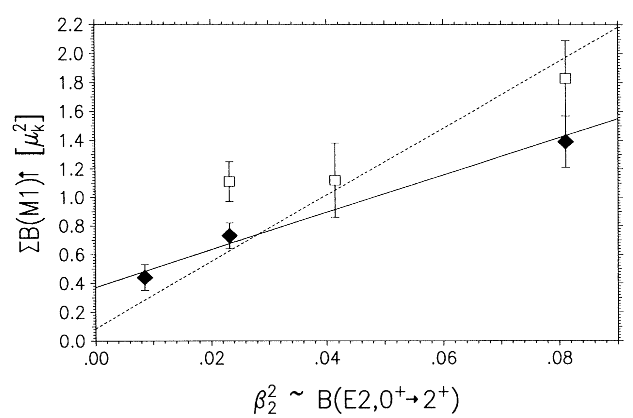

FIG. 2. Total $M1$ strength observed in the even Nd isotopes in the energy range 2–4 MeV as a function of the square of the deformation parameter β_2. Full symbols: Only transitions with known parity have been included. Open symbols: Summed strengths of all transitions from spin 1 states with decay branching ratios $R_{\text{exp}} \le 1$ corresponding to K=1 states within the validity of the Alaga rules. The full line represents a fit to the data with determined parities (full symbols, including the ^{148}Nd point). For comparison the dashed straight line shows the deformation dependence observed by the Darmstadt group for the even Sm isotopes [6].

TABLE III. Experimental data for ^{146}Nd obtained in this work for the total strength of excitations in the energy range 2–4 MeV. Taking into account all states with a branching $R_{\mathrm{exp}} < 1$ in the same energy range (open symbols in Fig. 2) one ends up with $\Sigma B(M1)\uparrow = (1.11 \pm 0.14)\mu_k^2$ (with the same detection limits as for the other Nd isotopes [5]). The total strength of transitions determined to have positive parities (full symbols in Fig. 2) amounts to $\Sigma B(M1)\uparrow = (0.73 \pm 0.09)\mu_k^2$. (no B. = no observed branching.)

Energy (keV)	R_{exp} ([5])	R_{exp}	Γ_0 (meV)	$B(M1)\uparrow$ (μ_k^2)	J^π
2356	0.61 ± 0.08	0.71 ± 0.09	17.2 ± 2.2	0.341 ± 0.043	1^+
2598	not observed	0.61 ± 0.27	2.5 ± 0.5	0.037 ± 0.008	?
2830	no B.	0.30 ± 0.13	5.8 ± 0.9		1^-
3276	0.52 ± 0.11	0.39 ± 0.06	16.3 ± 2.4	0.120 ± 0.017	1^+
3411	0.38 ± 0.06	0.45 ± 0.06	41.7 ± 6.1	0.273 ± 0.040	1^+
3577	0.93 ± 0.09	0.70 ± 0.10	45.2 ± 7.2	0.256 ± 0.041	$1^{(+)}$
3634	no B.	0.69 ± 0.15	12.4 ± 2.3	0.067 ± 0.012	1
3751	no B.	0.48 ± 0.09	20.5 ± 3.6		1^-
3780	no B.	0.19 ± 0.06	17.5 ± 3.1	0.084 ± 0.015	1
3798	1.23 ± 0.29	0.64 ± 0.14	15.2 ± 3.0	0.072 ± 0.015	1
3893	no B.	0.23 ± 0.12	25.9 ± 5.2	0.114 ± 0.023	1
3975	0.32 ± 0.17	0.34 ± 0.09	21.8 ± 4.7	0.090 ± 0.020	1

TABLE IV. Experimental data for ^{148}Nd obtained in our previous experiment [5]. The total strength of all states with a decay branching $R_{\mathrm{exp}} < 1$ in the energy range 2–4 MeV amounts to $\Sigma B(M1)\uparrow = (1.12 \pm 0.26)\mu_k^2$.

Energy (keV)	R_{exp}	Γ_0 (meV)	$B(M1)\uparrow$ (μ_k^2)	J^π
2376	0.98 ± 0.30	4.8 ± 1.0	0.09 ± 0.02	1
2923	0.85 ± 0.25	8.0 ± 2.1	0.08 ± 0.02	1
3215	0.32 ± 0.12	16.6 ± 3.1	0.13 ± 0.02	1
3341	0.60 ± 0.13	29.2 ± 5.4	0.20 ± 0.04	1
3370	0.70 ± 0.25	8.4 ± 2.2	0.06 ± 0.02	1
3405	0.67 ± 0.18	11.4 ± 2.8	0.07 ± 0.02	1
3528	0.80 ± 0.37	7.3 ± 2.4	0.04 ± 0.01	$(1,2^+)$
3545	0.68 ± 0.40	10.6 ± 3.3	0.06 ± 0.02	1
3597	0.73 ± 0.31	12.4 ± 3.5	0.07 ± 0.02	(1)
3717	0.49 ± 0.36	14.4 ± 4.4	0.07 ± 0.02	(1)
3861	0.19 ± 0.08	56.4 ± 11.8	0.25 ± 0.05	1

TABLE V. Experimental data for ^{150}Nd obtained in our previous experiments [5, 16–18] for the total strength in the energy range 2–4 MeV. Taking into account all states with branching ratios $R_{\mathrm{exp}} < 1$ in the same energy range (open symbols in Fig. 2) one ends up with $\Sigma B(M1)\uparrow = (1.83 \pm 0.26)\mu_k^2$. The total strength of excitations determined to have positive parities in the energy range 2–4 MeV (full symbols in Fig. 2) amounts to $\Sigma B(M1)\uparrow = (1.39 \pm 0.18)\mu_k^2$.

Energy (keV)	R_{exp}	Γ_0 (meV)	$B(M1)\uparrow$ (μ_k^2)	J^π
2681	0.79 ± 0.20	7.0 ± 1.4	0.09 ± 0.02	1
2895	0.58 ± 0.08	12.1 ± 1.7	0.13 ± 0.02	1^+
2994	0.56 ± 0.05	67.0 ± 7.3	0.65 ± 0.07	1^+
3058	0.48 ± 0.03	38.2 ± 4.3	0.35 ± 0.04	1^+
3096	0.92 ± 0.18	14.9 ± 3.0	0.13 ± 0.03	1^+
3103	0.68 ± 0.10	14.4 ± 2.2	0.13 ± 0.02	1^+
3342	0.34 ± 0.10	11.8 ± 2.1	0.08 ± 0.01	(1)
3642	0.96 ± 0.30	9.2 ± 2.7	0.05 ± 0.01	1
3711	0.82 ± 0.19	18.9 ± 4.2	0.10 ± 0.02	(1)
3751	0.86 ± 0.14	24.4 ± 4.7	0.12 ± 0.02	1

have negative parities ($E1$ transitions).

All numerical data of the present experiment and our previous investigations of even Nd isotopes are compiled in Tables II–V. The quoted errors of the $B(M1)\uparrow$ values contain both statistical and systematic errors. The uncertainties given for the total $M1$ strengths are calculated by adding the errors linearly.

The strong dipole excitations in the transitional nucleus ^{146}Nd have decay branchings which are in surprisingly good agreement with predictions from the Alaga rules valid in the rotational limit. Therefore, in Fig. 2 for comparison the strengths of all excitations are added up which show a decay branching $R_{\rm exp} < 1$ corresponding to $\Delta K = 1$ transitions in rotational nuclei, including weak transitions where no parity assignments could be achieved. Figure 2 shows the total strengths added up in the energy range 2–4 MeV observed in the Nd isotopes (^{142,146,148,150}Nd). Full symbols correspond to $M1$ strengths of transitions with reliable parity assignments from our linear polarization measurements or from literature; open symbols correspond to total strengths obtained by adding up the strengths of all dipole transitions in the energy range of interest ($E_\gamma = 2-4$ MeV) showing a $R_{\rm exp} \leq 1$ decay branching. The full line represents a fit to the data with determined parities (full symbols, including the ^{148}Nd point). The fact that the full line does not intersect zero is due to the inclusion of the 4095 keV 1^+ state in ^{142}Nd which has the same structure as the 3.97 MeV level in the isotone ^{144}Sm. It should be emphasized that the slope of the linear dependence fitted to the experimental data is strongly influenced by the experimental detection sensitivity (number of added up weak transitions of unknown parities). Consideration of all $\Delta K = 1$ transitions in the energy range of interest (open symbols), what seems to be reasonable in particular in the case of the well deformed nucleus ^{150}Nd, obviously would increase the slope and lead to a remarkable overall agreement with the Darmstadt Sm results. For comparison the linear dependence on β_2^2 of the total $M1$ strengths observed for the Sm isotopes in the Darmstadt experiments [6] is plotted as dashed line. Therefore, the new Nd results represent a reliable independent confirmation of the proposed δ^2 law [6].

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