First Measurement of the Monopole Strength in the Well-deformed Rare Earth Isotopes ^{154}Sm and ^{166}Er

K. Wimmer, V. Bildstein, R. Gernhäuser, D. Habs, Ch. Hinke, H. Hübel [a], Th. Kröll, R. Krücken, R. Lutter, H.J. Maier, P. Maierbeck, T. Morgan, O. Schaile, W. Schwerdtfeger, and P.G. Thirolf
[a] Rheinische Friedrich-Wilhelms-Universität Bonn

So far little experimental data is available on E0 matrix elements in well-deformed nuclei. Calculations using the interacting-boson approximation (IBA) predict a sharp increase in the monopole strength $\rho^2(\mathrm{E0}; 0_2^+ \to 0_1^+)$ in this phase transitional regime (in agreement with experimental data), which then remains large for well deformed nuclei [1] (see Fig.1). The latter prediction has so far not been experimentally confirmed, providing the motivation for our experimental study.

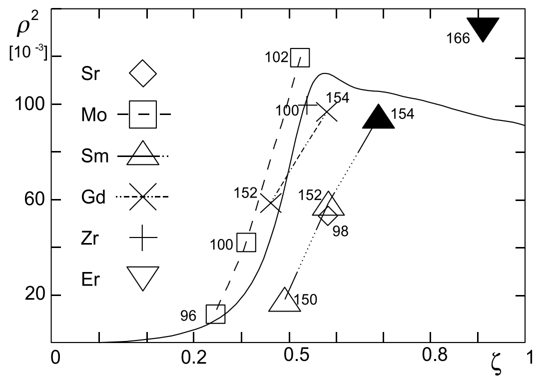

Fig. 1: Empirical $\rho^2(\mathrm{E0}; 0_2^+ \to 0_1^+)$ values for nuclei in shape transition regions and schematic IBA-1 calculations [1]. Our measurements for ^{154}Sm and ^{166}Er are marked with full symbols.

The Interacting Boson Approximation is a phenomenological model to describe nuclear structure in even-even nuclei. Pairs of valence nucleons are coupled to L=0 s-bosons and L=2 d-bosons. The parameter space is represented by a triangle (Fig.2) with the dynamical symmetries U(5) (vibrator), SU(3) (deformed rotor) and O(6) (γ-soft) marking the corners of the triangle.

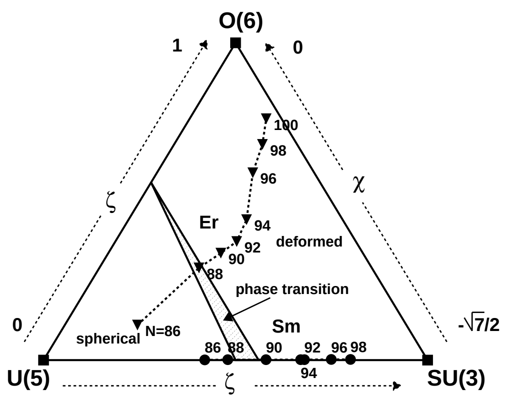

Fig. 2: Symmetry triangle ("Casten triangle") of the IBA model, trajectories for Er and Sm isotopic chains. The spherical-deformed phase transition at $\zeta \sim 0.54$ is indicated by the shaded region.

The only known $\rho^2(\mathrm{E0}; 0_2^+ \to 0_1^+)$ values in deformed rare earth nuclei (^{166}Er and ^{172}Yb) are very small ($\rho^2 \approx 2{\cdot}10^{-3}$) in contrast to the IBA predictions. However, the empirical 0_2^+ state may not correspond to the 0_2^+ state of the IBA. Calculations based on the parameter fits by McCutchan [2] in the ECQF approximation predict 0^+ states at 1355, 1979 and 2451 keV with $\rho^2(\mathrm{E0}; 0_i^+ \to 0_1^+) \cdot 10^3$ values of 39, 113 and 1 for ^{166}Er. For ^{154}Sm with $\zeta = 0.68$ IBA calculations predict a 0^+ state at 1089 keV with a $\rho^2(\mathrm{E0}; 0_2^+ \to 0_1^+) \cdot 10^3 = 115$. The model fails to predict the low-lying second excited 0_3^+ level at 1202 keV, instead this level is predicted to be at 1892 keV with $\rho^2(\mathrm{E0}; 0_3^+ \to 0_1^+) \cdot 10^3 = 5$.

Excited states in ^{154}Sm and ^{166}Er were populated via safe Coulomb excitation using self-supporting targets (760 and 995 μg/cm^2) and an ^{16}O beam at the MLL tandem accelerator(E_{lab}=60 and 55 MeV). Scattered particles were detected in a 64-fold segmented DSSSD in backward direction (covering angles from 152° to 170°), while the electrons were registered in a cooled Si(Li) detector in conjunction with a Mini-Orange spectrometer. Simultaneously the γ-rays emitted by the excited nuclei were detected with a MINIBALL triple-cluster Germanium detector. A sketch of the setup is shown in Fig.3.

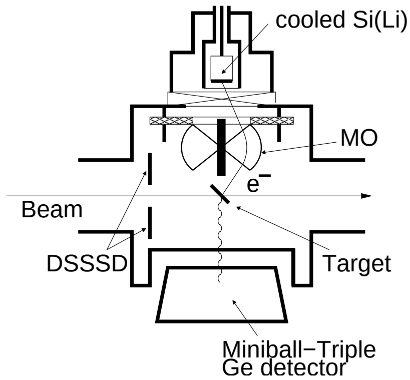

Fig. 3: Sketch of the experimental setup used at the MLL. Electron and γ-detectors were positioned perpendicular to the beam line, backscattered ^{16}O nuclei were registered in an annular DSSSD at backward angles.

The Mini-Orange [3] consists of 8 wedge-shaped permanent magnets arranged around a central Pb absorber and thus give a toroidal field of 160 mT. The transmission curve of the Mini-Orange was optimized for the expected E0 transition of 1053 keV in ^{154}Sm. For ^{166}Er the maximum was shifted to 1700 keV in order to measure the expected E0 transitions at 1402, 1656 and 1877 keV simultaneously.

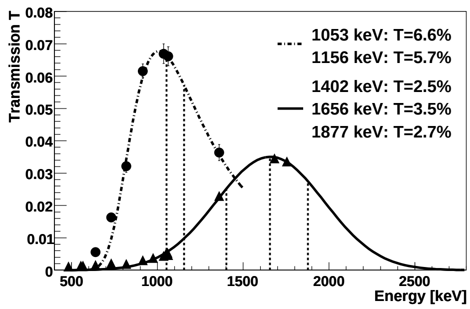

Fig. 4: Transmission curve of the Mini-Orange spectrometer. The maximum is at 1 MeV for ^{154}Sm, for ^{166}Er the curve is centered around 1.7 MeV by variation of the position of the MO with respect to target and Si(Li) detector.

The partial lifetime $\tau(\mathrm{E0})$ is given by the electric monopole strength $\rho^2(\mathrm{E0})$ and the non-nuclear electronic factors Ω_i:

$$\frac{1}{\tau(\mathrm{E0})} = \rho^2(\mathrm{E0}) \cdot (\Omega_\mathrm{K} + \Omega_\mathrm{L} + \ \ldots + \Omega_\mathrm{IP})$$

Experimentally the monopole strength is determined by the ratio of E0 and E2 K-conversion intensities q^2_K and the E2 transition rate $\mathrm{W}_\gamma(\mathrm{E2})$ [4].

$$\rho^2(\mathrm{E0}) = \mathrm{q}^2_\mathrm{K}(\mathrm{E0/E2}) \cdot \frac{\alpha_\mathrm{K}(\mathrm{E2})}{\Omega_\mathrm{K}(\mathrm{E0})} \cdot \mathrm{W}_\gamma = \frac{\mathrm{I_K(E0)}}{\mathrm{I_K(E2)}} \cdot \frac{\alpha_\mathrm{K}(\mathrm{E2})}{\Omega_\mathrm{K}(\mathrm{E0})} \cdot \frac{1}{\tau_\gamma}$$

The conversion coefficients α_K and the electronic factors Ω_K are tabulated, the lifetime of the excited 0^+ states is known by previous experiments.

Garrett et al. measured the lifetimes and B(E2)-values for the first three excited 0^+ states in ^{166}Er [5]. Since the 0^+_4 state has a much larger B(E2) value to the ground state band of 8.8(9) W.u., compared to the 0^+_2 state (2.7(10) W.u.) they interpret the 0^+_4 state as the β vibration [5]. It is expected to have a much larger $\rho^2(\mathrm{E0})$ compared to the 0^+_2 state ($\rho^2(\mathrm{E0}) \cdot 10^3 = 2.2(8)$ [4]).

The 0^+ levels at 1460 and 1934 keV have been populated in the Coulomb excitation reaction, their γ-transitions to the 2^+ state of the ground state band are visible in the γ-spectrum. The excitation probability for the 0^+_3 state at 1713 keV is at least a factor of 8 lower, it has not been excited significantly.

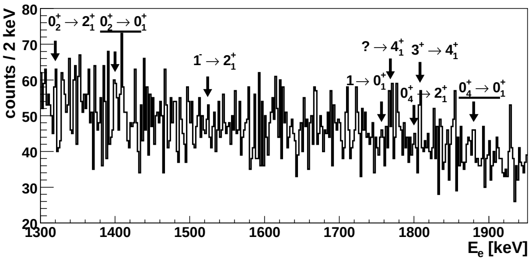

Fig. 5: Conversion electron energy spectrum for ^{166}Er, the E0 transitions are underlined.

Due to poor statistics (21 counts in 35 h in the $0^+_2 \rightarrow 0^+_1$ line) it was not possible to require a coincidence with particles hitting the DSSSD for the analysis of the conversion electron spectrum. Therefore the intensities have large statistical uncertainties.

With $\alpha_\mathrm{K} = 1.505 \cdot 10^{-3}$, $\Omega_\mathrm{K} = 1.201 \cdot 10^{11}$ 1/s [6] and a partial lifetime $\tau_\gamma = 1.1(4)$ ps for the first excited 0^+ state a value of $\rho^2(\mathrm{E0}) \cdot 10^3 = 5.2(31)$ could be deduced in agreement with the known value of 2.2(8).

For the third excited 0^+ level at 1934.4 keV the lifetime is only 78(8) fs. A conversion coefficient $\alpha_\mathrm{K} = 8.72 \cdot 10^{-4}$ and electronic factor of $\Omega_\mathrm{K} = 1.638 \cdot 10^{11}$ 1/s gives $\rho^2(\mathrm{E0}) \cdot 10^3 = 137(81)$.

By increasing the beam energy to 65 MeV we can achieve a factor of 4 higher excitation probabilities for the 0^+ states. In a forthcoming experiment (4 days beam time) we aim at increasing statistics by at least a factor of 10, thus reducing statistical uncertainties significantly.

In ^{154}Sm the $0^+_2 \rightarrow 0^+_1$ and the $2^+_2 \rightarrow 2^+_1$ transitions are only 4 keV apart. With our detector resolution of 4.6 keV they can not be separated unambiguously. Coulomb excitation calculations reveal that for particles hitting the DSSSD the excitation probability for the 0^+_2 state is a factor 13.3 larger than for the 2^+_2 state. Thus the $2^+_2 \rightarrow 2^+_1$ transition can be neglected for the determination of the monopole strength.

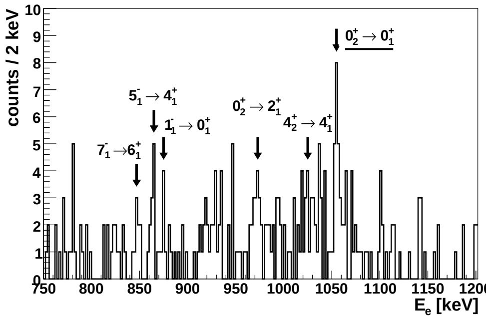

Fig. 6: Background-subtracted ^{154}Sm conversion electron energy spectrum in coincidence with particles hitting the DSSSD.

The measured lifetime of 1.3(3) ps [7], resulting in a B(E2)-value of 12(2) W.u., leads to the identification as the β-vibrational excitation of the ground state. The electronic factor for the $0^+_2 \rightarrow 0^+_1$ transition is $\Omega_\mathrm{K} = 3.688 \cdot 10^{10}$ 1/s, the conversion coefficient for the 1018 keV $0^+_2 \rightarrow 2^+_1$ transition is $\alpha_\mathrm{K} = 2.045 \cdot 10^{-3}$. This results in a transition strength of $\rho^2(\mathrm{E0}) \cdot 10^3 = 95(43)$. For the second excited 0^+ state at 1202 keV only an upper limit of 0.3 W.u. for the B(E2; $0^+_3 \rightarrow 2^+_1$) is known. This state is only weakly populated in the Coulomb excitation reaction although it is only 103 keV above the 0^+_2 state. With an upper limit for the observed intensity of 50 counts in 55 h run time a limit for its transition to the ground state of $\rho^2(\mathrm{E0}) \cdot 10^3 < 5.0$ can be obtained.

For the first time large $\rho^2(\mathrm{E0})$ values in well-deformed rare earth nuclei were experimentally determined (see Fig. 1).

transition	$\rho^2(\mathrm{E0}; 0^+_\mathrm{i} \rightarrow 0^+_1) \cdot 10^3$	
	this work	IBA
$0^+_2 \rightarrow 0^+_1$	95(43)	115
$0^+_3 \rightarrow 0^+_1$	< 5.0	5

Table 1: Summary of the measured $\rho^2(\mathrm{E0})$ values and IBA calculations for ^{154}Sm.

The measured values for ^{154}Sm summarized in table 1 are consistent with the IBA predictions. ^{154}Sm represents one of the rare cases, where the lowest 0^+ state of a deformed nucleus is indeed a collective β-vibrational excitation of the ground state.

For ^{166}Er the results are summarized in table 2. The comparison of the B(E2) values to the ground state band in table 2 allows for the assumption that the 0^+_3 state of the IBA could be assigned to the empirical 0^+_4 state.

	B(E2; $0^+_\mathrm{i} \rightarrow 2^+_1$)		$\rho^2(\mathrm{E0}; 0^+_\mathrm{i} \rightarrow 0^+_1) \cdot 10^3$		
	exp. [W.u.]	IBA [a.u.]	this work	prev.	IBA
0^+_2	2.7(10)	0.72	5.2(31)	2.2(8)	39
0^+_3	< 0.8	0.04	-	-	113
0^+_4	8.8(9)	0.01	131(78)	-	1

Table 2: Summary of the measured $\rho^2(\mathrm{E0})$ and B(E2) values and IBA calculations for ^{166}Er.

The large $\rho^2(\mathrm{E0})$-value of the third excited 0^+ state in ^{166}Er confirms its interpretation as the β-vibration of the ground state.

References

[1] P. von Brentano *et al.*, Phys. Rev. Lett **93** (2004) 152502
[2] E. A. McCutchan *et al.*, Phys. Rev. **C69** (2004) 064306
[3] J. van Klinken and K. Wisshak, Nucl. Instr. Meth. **98** (1972) 1
[4] T. Kibédi and R. H. Spear, ADNDT **89** (2005) 77
[5] P. E. Garrett *et al.*, Phys. Lett. **B400** (1997) 250
[6] J. Kantele, Handbook of nuclear spectrometry
[7] R. Krücken *et al.*, Phys. Lett. **B454** (1999) 15