Shape Coexistence at the Borderline of the 'Island of Inversion': First Identification of the E0 Decay from the Deformed 0_2^+ State in ^{30}Mg ◇

W. Schwerdtfeger, P.G. Thirolf, K. Wimmer, D. Habs, H. Mach [a], V. Bildstein, L.M. Fraile [b], R. Gernhäuser, K. Heyde [c], P. Hoff [d], U. Köster [e], T. Kröll, R. Krücken, R. Lutter, T. Morgan, and P. Ring

[a] Department of Radiation Sciences, Uppsala University, Sweden [b] CERN, Geneva, Switzerland
[c] Department of Subatomic and Radiation Physics, Universiteit Gent, Belgium
[d] Department of Chemistry, University of Oslo, Norway [e] ILL, Grenoble, France

A shape coexistence of spherical and deformed 0^+ states is predicted to exist around the ‚island of inversion' in neutron-rich Mg isotopes. While the closed-shell nucleus ^{32}Mg exhibits a highly deformed ground state ($\beta \sim 0.51$), the ground state of ^{30}Mg is expected to be much less deformed. The (deformed) excited 0^+ state is predicted by theory between 1.7 and 2 MeV [1] but has not yet been observed experimentally. However, recent experimental findings create confidence that the experimental identification of shape coexistence in ^{30}Mg is within reach. Resulting from fast timing γ-spectroscopy studies [2] the 1789 keV level in ^{30}Mg emerged as a strong candidate for the deformed first excited 0^+ state due to its long lifetime of 3.9 ns and the absence of a ground state γ transition, as can be seen in the level scheme of ^{30}Mg shown in Fig. 1. This triggered our search for the deformed 0_2^+ state in ^{30}Mg via conversion electron spectroscopy within the framework of the ISOLDE IS414 collaboration.

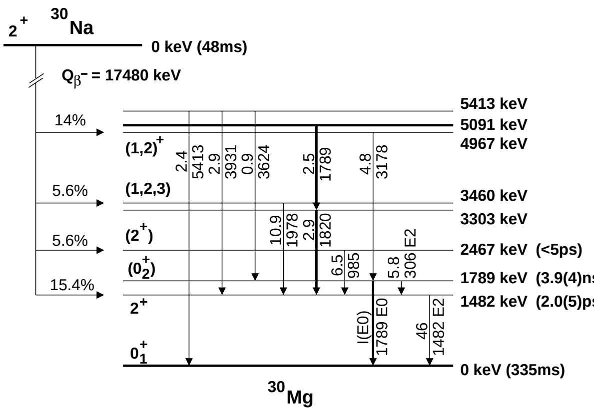

Fig. 1: Low-energy part of the level scheme of ^{30}Mg following β decay of ^{30}Na according to [2].

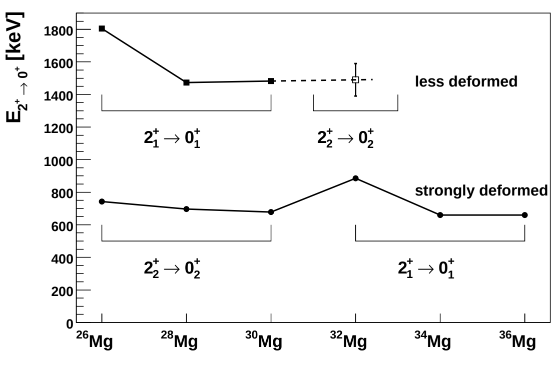

Fig. 2: Systematics of strongly deformed and spherical (or much less deformed) $2^+ \rightarrow 0^+$ transitions.

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As a result of previous experiments already described in [3,4] it turned out that the E0 transition strength is much weaker than initially expected and the first coincidence experiment revealed that the background surviving the coincidence condition had to be reduced. Different test measurements and GEANT4 simulations were performed to identify sources of the remaining background described in [4], resulting in a completely new built target chamber consisting of aluminum with 10 mm thick walls covered with 15 mm Teflon at the inner side to reduce scattering and to absorb Compton-scattered electrons. The Ge-detector was retracted and the thickness of the plastic β scintillator was reduced to 0.2 mm in order to minimize its sensitivity to γ rays.

Since the halflife of ^{30}Na (48 ms) is much shorter compared to the contaminants ^{30}Mg (335 ms) or ^{30}Al (3600 ms) events with short lifetimes ($\leq$ 500 ms) were selected from a decay time measurement relative to the initial proton pulse, thus enhancing spectral contributions from the β-decay of ^{30}Na.

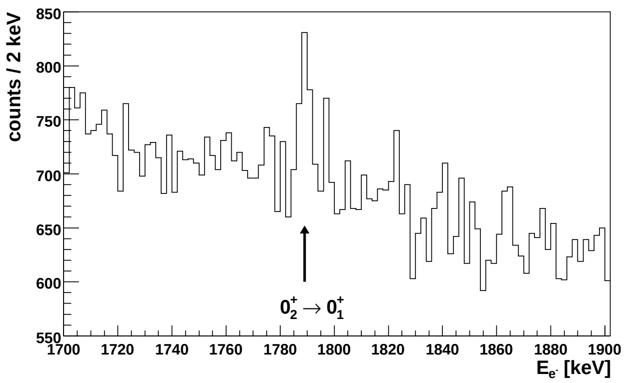

Fig. 3: Background-subtracted conversion electron spectrum measured in coincidence with β decay signals in the plastic detector. Also the short halflife of the ^{30}Na decay was used to reduce the background.

The resulting conversion electron spectrum detected with the Si(Li) detector in coincidence with β-decay electrons is shown in Fig. 3. The searched $0_2^+ \rightarrow 0_1^+$ E0 transition at 1788 keV is clearly visible. 335(62) counts could be detected in the peak during 143 hrs of beamtime. With an energy resolution of 3.0 keV for the Si(Li) detector spanning K and L conversion in ^{30}Mg (E_K =1.3 keV), the monopole strength ρ^2(E0) can be determined by the ratio of E0 and E2 (K+L) conversion intensities and the lifetime τ of the 0_2^+ state as [5]

$$\rho^2(\mathrm{E0}) = \frac{I_{\mathrm{K+L}}(\mathrm{E0})}{I_\gamma(\mathrm{E2})} \cdot \frac{1}{\Omega_{\mathrm{K+L}}(\mathrm{E0})} \cdot \frac{1}{\tau}. \quad (1)$$

The γ intensity of the E2 transition at 306 keV measured within the β - γ coincidence condition using the Ge detector is $I_\gamma(\mathrm{E2}) = 2.1 \cdot 10^3$ ($\epsilon_\gamma = 0.0019$), the lifetime τ of the 0_2^+ state was measured to be 3.9(4) ns [2] and the electronic Ω factors are $\Omega_{K+L} = 1.39 \cdot 10^7$/s [6]. This finally allows to derive the monopole matrix element as $\rho^2(\mathrm{E0},{}^{30}\mathrm{Mg}) = 5.7(12) \cdot 10^{-3}$. In order to determine the mixing of the 0^+ states it is necessary to describe the large $B(E2)$ value of the $2_1^+ \to 0_1^+$ ground state transition (241(31) $\mathrm{e}^2\mathrm{fm}^4$ [8]) and the small value of the electric monopole strength $\rho^2(\mathrm{E0})$ in a consistent way. Assuming the ground state to be spherical or much less deformed than the 0_2^+ state, the small $\rho^2(\mathrm{E0})$ value indicates only a weak admixture of the deformed 0_2^+ state. This is in disagreement with the large $B(\mathrm{E2})$ value, which suggests a rather deformed 0_1^+ ground state.

This discrepancy can be resolved by invoking the Grodzins systematics, which empirically correlates the B(E2) value and the excitation energy of the first excited 2^+ state. Using the parameterization by Raman et al. [7] this correlation is given as

$$B(\mathrm{E2}) \cdot E(2_1^+) = (2.57 \pm 0.45) \cdot Z^2 \cdot A^{-2/3}. \quad (2)$$

Over a wide range of the chart of nuclei this systematics successfully allows to predict B(E2) values from 2^+ energies within a factor of 2. For ^{30}Mg and ^{32}Mg the B(E2) values predicted by the Grodzins systematics (245 $\mathrm{e}^2\mathrm{fm}^4$ and 410 $\mathrm{e}^2\mathrm{fm}^4$) agree remarkably well with the experimental ones (241(31) $\mathrm{e}^2\mathrm{fm}^4$ [8] and 454(78) $\mathrm{e}^2\mathrm{fm}^4$ [9]). This points to rather pure states in the two potential minima, because otherwise deviations from the Grodzins systematics could be expected. In turn this allows to derive the (effective) deformation of the 0^+ ground state in ^{30}Mg and ^{32}Mg from the B(E2) values in the rigid rotor model using

$$\beta = \left(\frac{4\pi}{eZR^2}\right) \cdot \left(\frac{B(\mathrm{E2})}{e^2}\right)^{1/2} \quad (3)$$

with $R = 1.2\ \mathrm{fm}\cdot A^{1/3}$, resulting in $\beta = 0.39$ for ^{30}Mg and $\beta = 0.51$ for ^{32}Mg.

Within the quadrupole deformed rigid rotor model and assuming a two-level system with mixing amplitude a, the strength of the connecting E0 transition between two different equilibrium quadrupole deformations (β_1, β_2) can be described as [10]

$$\rho^2(E0) = (\frac{3}{4\pi}Z)^2 \cdot a^2 \cdot (1 - a^2) \cdot (\beta_1^2 - \beta_2^2)^2 \quad (4)$$

While the ground state deformation $\beta_1 = 0.39$ in ^{30}Mg was derived as discussed above, the deformation of the 0_2^+ state can be determined from the level scheme of ^{30}Mg (Fig. 1) with the assignment of the 2467 keV level as being the deformed 2_2^+ state. This assignment is supported by the smoothly varying systematics of the strongly deformed $2^+ \to 0^+$ transition energies in the Mg isotopes (with the exception of the intruder configuration in ^{32}Mg, see Fig. 2). From the resulting $2_2^+ \to 0_2^+$ transition energy of 678 keV a deformation according to Eq. 3 of $\beta_2 = 0.57$ can be extracted. Hence according to Eq. 4 in Fig. 4 the correlation between the electric monopole stength $\rho^2(E0)$ and the squared mixing amplitude a^2 is displayed for ^{30}Mg.

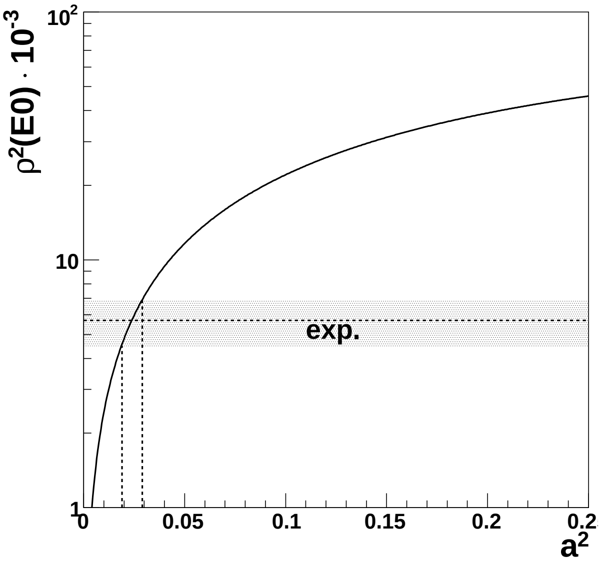

Fig. 4: Dependence of ρ^2 on the squared mixing amplitude for ^{30}Mg. The dash-dotted lines indicate the value of the experimentally determined monopole strength with its error margin.

From the experimental value of $\rho^2(E0)$ a value of $a^2 = 0.023(5)$ can be extracted, resulting in a rather small value of $a = 0.15(2)$ for the mixing amplitude between the two 0^+ states.

Thus for the first time the mixing amplitude between shape-coexisting 0^+ states in the region of the ,Island of Inversion' could be deduced.

As result of our experiment the picture of the potential barrier in ^{30}Mg has to be revised, since the 0^+ ground state in ^{30}Mg turns out not to be spherical as so far expected. In contrast a consistent description of the small electric monopole strength together with the large quadrupole collectivity can only be achieved when assigning a rather large (effective) deformation of $\beta = 0.39$ to the ground state in ^{30}Mg.

More detailed microscopic calculations [1,11,12,13], which presently are not able to provide a quantitatively satisfying description of our experimental findings will hopefully be able to give a better insight into the particullary large $B(\mathrm{E2})$ and small ρ^2 value as obtained from previous experiments.

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