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Collectivity and single-particle degrees of freedom

Studies of light $f_{7/2}$ nuclei at EUROBALL IV and recoil filter detector

P. Bednarczyk[1,2,a], J. Styczeń[2], A. Bracco[3], D. Curien[1], J. Grębosz[2], M. Lach[2], A. Maj[2], J.C. Merdinger[1], W. Męczyński[2], F. Nowacki[1], M.B. Smith[4,b], K. Spohr[4], J.P. Vivien[1], and M. Zięblński[2]

[1] Institut de Recherches Subatomiques, Strasbourg, France
[2] H. Niewodniczański Institute of Nuclear Physics, Kraków, Poland
[3] Università degli Studi di Milano and INFN, Milano, Italy
[4] University of Paisley, Paisley, Scotland, UK

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Abstract. Intruder rotational bands in ^{45}Sc and ^{45}Ti have been investigated up to the maximum aligned angular momentum by means of EUROBALL IV and the Recoil Filter Detector (RFD). The use of the RFD allowed for a reduction of the γ-line Doppler broadening and, moreover, for a determination of very short level lifetimes. In the studied nuclei, the estimated deformation shows a gradual disappearance of the collectivity at the highest available spins.

PACS. 21.10.Tg Lifetimes – 21.60.Cs Shell model – 27.40.+z $39 \leq A \leq 58$

Superdeformation observed in the ^{36,38}Ar and ^{40}Ca nuclei [1–4] is a feature rather expected even for such light nuclei. Recently, both the shell model and the cluster model [4] have predicted for light nuclei the existence of very deformed states, *i.e.* having a very large quadrupole moment and connected by fast $E2$ transitions which could be associated with the observed SD bands.

In the theoretical description, the superdeformation in nuclei around ^{40}Ca requires a significant contribution of rather complicated multi-particle multi-hole core excitations. Unlikely, in the vicinity of ^{48}Cr, in the middle of the $f_{7/2}$-shell, the observed rotational behaviour is well accounted for by calculations restricted to the valence nucleons in the extended fp-shell [5]. In light odd-A $f_{7/2}$-shell nuclei as ^{45}Sc or ^{45}Ti, intruder rotational bands with an intermediate deformation result from a coupling of the valence fp nucleons and particle-hole excitations across the closed-shell gap [6]. Investigation of such structures allows for a better understanding of the role played by single-particle degrees of freedom in creating nuclear collectivity.

The high-spin states in the ^{45}Sc and ^{45}Ti nuclei, and several neighbouring nuclei were populated in a fusion-evaporation reaction at the VIVITRON tandem accelerator of IReS in Strasbourg. A 68 MeV ^{18}O beam bombarded a 0.8 mg/cm^2 ^{30}Si target. Gamma rays were measured in the EUROBALL IV array. The velocity vector of every recoiling nucleus was determined by the Recoil Filter Detector. This provided a very efficient way to reduce γ-line Doppler broadening and allowed the observation of high-energy γ-rays with good resolution [7].

The γ-recoil coincidences were also helpful in a better selection of the reaction plane, thus improving the sensitivity on the γ-ray polarisation and the angular distribution. In our experiment, due to the application of the RFD, short lifetimes could be estimated. The method takes advantage of the difference between the velocity vector measured by the RFD for the recoil emitting a γ-ray while straggling inside the target and for the recoil emitting that γ-ray after its escape from the target. In the first case, the insufficient Doppler correction trails the γ-line in the spectrum. A probability of the γ-emission in vacuum can be expressed by a ratio of the mean level lifetime τ and the transit time T of the recoil passing through the target. Therefore, τ can be estimated from a contribution of the properly Doppler-corrected γ-rays to the total γ-line area. The range of measured lifetimes depends on T and can be chosen by the selection of the target thickness. In the experiment described here, for $T = 400$ fs, the lifetimes ranging from 40 fs to 800 fs have been determined.

The complete spectroscopic information on measured γ-rays obtained in the experiment allowed for a significant extension of the level schemes in the studied nuclei. In ^{45}Sc as previously reported [7], a termination of the rotational band built upon the $d_{3/2}^{-1} f_{7/2}^{6}$ configuration was observed. The lifetimes of the $J^{\pi}_{\max} = 31/2^{+}$ band terminating state and the $J^{\pi} = 35/2^{+}$ state lying above that state were determined. The evolution of the deformation

[a] *Present address*: GSI, Darmstadt, Germany; e-mail: P.Bednarczyk@gsi.de
[b] *Present address*: TRIUMF, Vancouver, Canada.

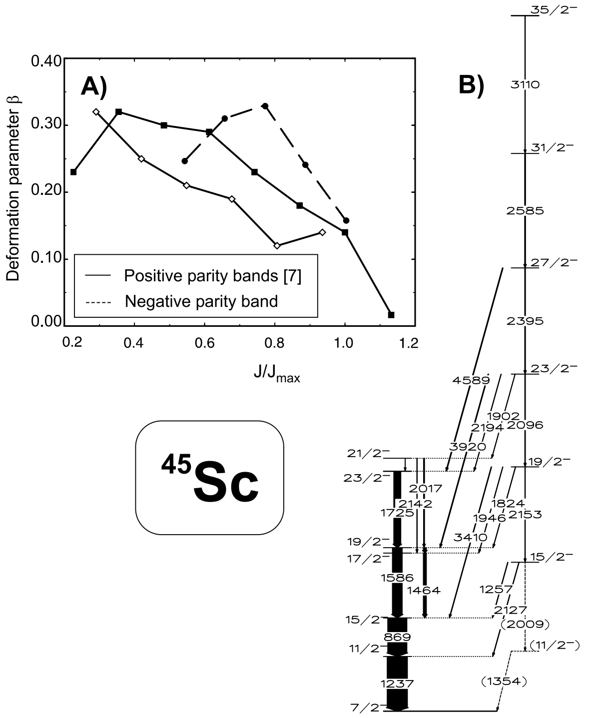

Fig. 1. A) The deformation parameter β for the positive- and negative-parity intruder bands in ^{45}Sc, as deduced from the lifetime analysis described in the text, *versus* spin relative to the maximum aligned angular momentum. B) A partial level scheme of ^{45}Sc. The figure shows the ground-state band and a new negative-parity rotational band based most likely on a $7p$-$2h$ configuration.

along the band is illustrated in fig. 1A), where the values of the deformation parameter β from the present work and ref. [6] are plotted as a function of spin relative to $J_{\max}$. Although at low and medium angular momenta the deformation is rather high with $\beta \approx 0.3$, it decreases when approaching the band termination. The nucleus loses gradually the collectivity and becomes spherical above the maximum aligned spin. This effect has been theoretically predicted by Poves *et al.* [8]. In ^{45}Sc a new negative-parity band, shown in fig. 1B), has been identified. The band extends up to the spin of $J^{\pi} = 35/2^{-}$, the maximum value available for a $7p$-$2h$ configuration. As shown in fig. 1A), the deformation associated with this new band exhibits similar behaviour in magnitude and trend at high spins as that of the $K^{\pi} = 3/2^{+}$ band. This effect may point out that the deformation in ^{45}Sc is not directly related to the number of involved particle-hole excitations.

The investigation of high-spin levels in ^{45}Ti has revealed the presence of two competing positive-parity bands of different single-particle structure. In fig. 2A), a partial level scheme of this nucleus is shown. Similarly to ^{45}Sc, the $K^{\pi} = 3/2^{+}$ band dominates in ^{45}Ti at lowest spins.

However, at higher angular momentum above the spin $J^{\pi} = 17/2^{+}$, the main decay path goes through a newly observed yrast band extended up to the maximum aligned spin of $J^{\pi} = 33/2^{+}$. The deformation parameter β obtained for those bands *versus* J is shown in fig. 2B). As

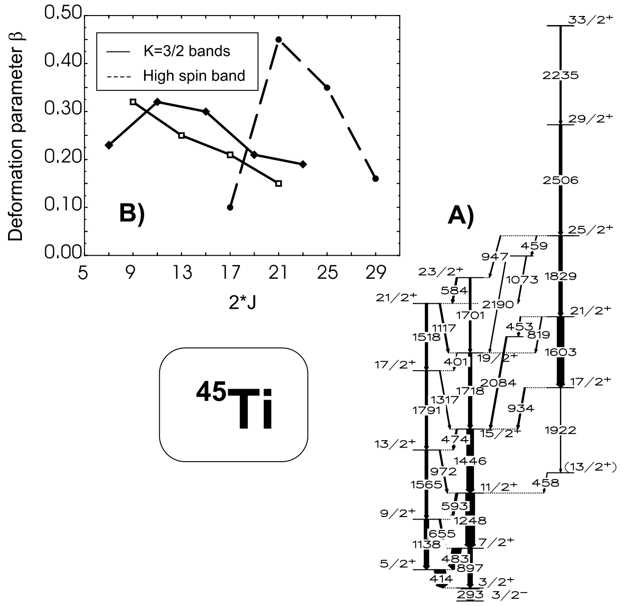

Fig. 2. A) A partial level scheme of ^{45}Ti. The newly observed band dominating at high spins resembles the $T = 0$ ground-state band in ^{46}V. B) The deformation parameter β for the low- and the high-spin rotational bands in ^{45}Ti as a function of spin.

one notices, it has a value close to $\beta \approx 0.3$ for the low-lying $K^{\pi} = 3/2^{+}$ bands, similarly to corresponding bands in ^{45}Sc. However, it reaches rather high value of $\beta \approx 0.45$ for the new yrast high-spin band with a decrease for the highest spins. We have performed extended shell model calculations for the ^{45}Ti nucleus. They predict coexistence of bands resulting from the excitation of a proton or neutron particle-hole coupled to the $f^{6}_{7/2}$ configuration. Moreover, a pure $\pi d^{-1}_{3/2} \otimes {}^{46}$V excitation is expected from these calculations. Indeed, the newly identified high-spin yrast band resembles the ground state $T = 0$ band in the $N = Z$ nucleus ^{46}V [9]. The high deformation associated with this structure in ^{45}Ti may suggest an important role of the p-n pairing that can increase the collectivity [10].

In summary, the complete γ-ray spectroscopy studies of ^{45}Sc and ^{45}Ti have provided new information on the high-spin excitations in these nuclei. In ^{45}Sc, a new $7p$-$2h$ band has been identified, whereas in ^{45}Ti, a strongly deformed band analogue to $T = 0$ ground-state band in the $N = Z$ nucleus ^{46}V has been observed. In both nuclei, the studied intruder rotational bands lose gradually the collectivity at high spins.

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