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The N = Z $f_{7/2}$-shell nuclei: Experimental highlights

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Abstract. During the last decade, as the experimental and computing means and techniques have rapidly evolved, the experimental investigation of the $f_{7/2}$-shell nuclei has gained renewed interest. The $N = Z$ nuclei studied with the GASP array range from ^{44}Ti to ^{52}Fe. The results extended the knowledge of their structure up to high spins and excitation energies, above band terminations, where the competition with the charged-particles emission was initially thought to obscure the possibility of gamma-ray spectroscopy investigation. The paper highlights some of the most outstanding properties of these nuclei such as the nuclear rotation and backbending effects, band termination states, yrast traps, non-natural parity bands, competition between $T = 0$ and $T = 1$ pn pairing modes.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.60.Cs Shell model – 23.20.Lv γ transitions and level energies – 27.40.+z $39 \leq A \leq 58$

1 Introduction

By $f_{7/2}$-shell nuclei one denotes those nuclei with proton numbers between the magic numbers 20 and 28. These nuclei form a unique island in the nuclide chart as they have a low number of active valence particles to allow for a full shell model description but already large enough to develop a collective behavior with all its consequences. Therefore, they constitute the ideal ground for comparing very different nuclear models, such as the shell model and mean-field calculations in the intrinsic reference system (*e.g.*, Cranked Hartree-Fock-Bogolyubov), within the same nucleus. The middle of the shell is characterized by large deformations near the ground state, but moving away toward the ends of the shell the collective behavior is replaced by single-particle effects. As the excitation energy increases, the single-particle degrees of freedom and the collective ones compete to produce band termination, shape changes and backbending effects. It is reasonable to assume that the structure of $N = Z$ nuclei will follow, generally, the same trend as that identified in the neighboring nuclei but it is expected to individuate characteristic fingerprints of the strong pn pairing correlations.

These nuclei are located close to the valley of stability and far enough from the proton drip line to be populated with relatively high cross-sections. This allowed the study of their high-spin structure and its evolution with the spin and excitation energy. Such studies were attempted also in the $N = Z$ nuclei neighboring the island of large deformation around $N = Z = 40$ but it resulted to be an extremely difficult task with the available experimental techniques. The results obtained for the $f_{7/2}$-shell $N = Z$ nuclei permitted the "calibration" of the nuclear models to include the proton-neutron pairing and to make realistic predictions on what one can expect to find in the heavier $N = Z$ nuclei.

Simple shell model calculations performed considering only the $f_{7/2}$-orbital gave a reasonable good description for the low-spin structure of the mass $A = 50$ nuclei. Discrepancies were found for the deformed nuclei where the other orbitals from the *pf*-shell had to be considered as well to reproduce the transition probability values. Recently, large-scale shell model calculations in the full *pf*-shell have become available providing a very accurate description of the nuclei in the middle of the $f_{7/2}$-shell. Non-natural parity bands were identified in all these nuclei; most of them are interpreted as due to a $(f_{7/2}d^{-1}_{3/2})$ particle-hole excitation. In some cases these structures were built up to the band termination in the $f^{n+1}_{7/2}d^{-1}_{3/2}$ configuration space.

In this paper I will present the most important experimental results obtained from the study of the $f_{7/2}$-shell $N = Z$ nuclei with the GASP detector array and their theoretical interpretation.

2 Experiments

Two decades ago, the study of the $f_{7/2}$-shell nuclei through fusion-evaporation reactions was restricted

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mainly to low spins due to experimental limits in the sensitivity and efficiency of the instruments. The investigation of high-spin states undergoes experimental difficulties due to: a) low angular momentum transferred via heavy-ion fusion-evaporation reactions because of the small masses of the reaction partners; b) the low Coulomb barrier leads to a large number of competing reaction channels with evaporation of charged particles; c) high velocities of the recoil nuclei (about 5% of the light speed), combined with kinematic effects due to the evaporation of charged particles, lead to a drastic increase of the gamma-ray peak widths; d) rapid increase with spin of the gamma-ray transition energies. The solution to these problems came forth with the advent of the last generation of large gamma-ray arrays and their associated ancillary detectors.

The GASP array [1] was one of the instruments actively used for the investigation of the $A = 50$ mass region. It consists of 40 HPGe detectors with anti-Compton shields that, in the standard configuration, allows for a 3% photopeak detection efficiency. A BGO calorimeter built of 80 elements, covering 80% of the solid angle, acts as a gamma-ray multiplicity and sum energy filter. The resulting observational limit of the array is of about 10^{-4}. For the study of the $f_{7/2}$-shell nuclei, of vital importance was the operation of the GASP array together with its ancillary charged-particle detector ISIS [2]. This detector consists of 40 E-ΔE Si telescopes for the identification of light charged particles. It covers about 75% of the solid angle and have a detection efficiency of about 65% for a proton and 35% for an alpha particle. The use of this detector allowed also for an event-by-event kinematical Doppler correction of the data improving strongly the quality of the spectra.

At the GASP array we have performed a systematic investigation of the $f_{7/2}$-shell nuclei populated through the reactions: ^{32}S + ^{24}Mg (self-supported thin target) at 130 MeV, ^{28}Si + ^{28}Si (gold-backed target) at 115 MeV and ^{28}Si + ^{24}Mg (self-supported thin target) at 100 MeV bombarding energy. New results were obtained for the $N = Z$ nuclei ranging from ^{44}Ti to ^{52}Fe. The high-spin structure was largely extended also for many nuclei neighboring the $N = Z$ line. The result was a complete image of the properties characterizing these nuclei with the structure dominated mainly by the single $f_{7/2}$-orbital.

3 Rotational bands, backbending, shape changes

The best rotor in the $f_{7/2}$-shell is the nucleus ^{48}Cr [3]. With its 8 valence particles (4 protons and 4 neutrons) above the double magic nucleus ^{40}Ca, it is located exactly in the middle of the $f_{7/2}$-shell and it has the maximum number of active particles available to develop a collective behavior. In particular, from lifetime measurements [4] it was shown to be well deformed with a quadrupole deformation parameter $\beta_2 \approx 0.3$. Figure 1 shows the level scheme of the nucleus. The rotational-like ground-state band has a backbending around spin 12^+ and terminates at spin 16^+. Large-scale shell model calculations

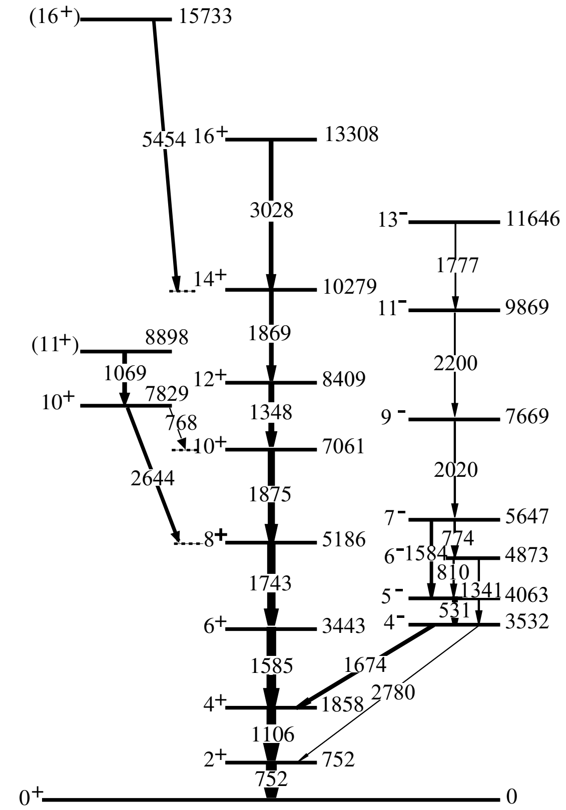

Fig. 1. Level scheme of the $N = Z = 24$ nucleus ^{48}Cr (from ref. [5]).

performed in the full pf-shell for this nucleus [6] gave an exact description of both the level structure and electromagnetic properties of the gamma-ray transitions.

In fig. 2 we plotted the spin *versus* the gamma-ray energy for the experimental data and the calculations with the large-scale shell model and the Cranked Hartree-Fock-Bogolyubov model (CHFB). It can be noticed that the CHFB calculations overestimates the moment of inertia resulting in a very compressed level scheme. This was interpreted [7] as being due to the incompleteness of the CHFB calculations where the proton-neutron pairing is not included. Furthermore, it was argued that both the isovector ($T = 1$) and the isoscalar ($T = 1$) pn pairing lead to the same effect of overestimating the moment of inertia if omitted from the calculations. On the other hand, electromagnetic properties are well reproduced by both calculations [6]. As demonstrated by Zuker *et al.* [8] the occurrence of deformation in the $f_{7/2}$ nuclei is related to the correlation between $\Delta j = 2$ orbitals $f_{7/2}$ and $p_{3/2}$ which are by far the dominant ones at low spin (see fig. 3). The CHFB analysis suggests at low spins a prolate deformation with $\beta_2 \approx 0.26$. At the backbending where the $f_{7/2}$ orbital becomes the only relevant one the deformation decreases. Above the backbending the nucleus becomes triaxial and at the band termination, where the contribution of the three orbitals $p_{3/2}$, $f_{5/2}$ and $p_{1/2}$ is practically reduced to zero, the nucleus becomes spherical.

In the case of the nucleus ^{52}Fe [9] the ground-state band does not have the regular behavior seen in ^{48}Cr.

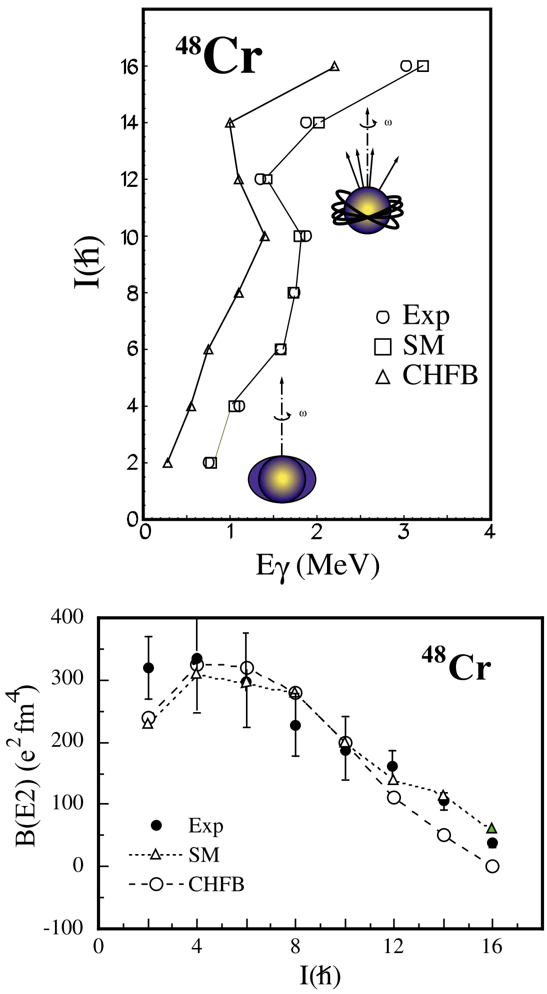

Fig. 2. Experimental data compared with the full shell model and Cranked Hartree-Fock-Bogolyubov calculations for the ground-state band of the ^{48}Cr nucleus.

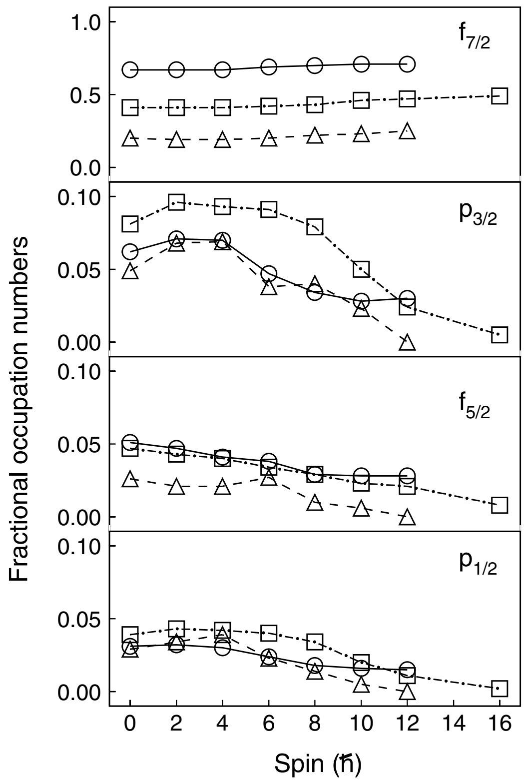

Fig. 3. Fractional occupation numbers of the pf-shell orbitals for the ground-state bands in ^{44}Ti (triangles), ^{48}Cr (squares), ^{52}Fe (circles) as extracted from the shell model calculations (from ref. [9]).

The structure up to spin $4\hbar$ can be considered as a rotor: the ratio of the excitation energies of the 4^+ and 2^+ yrast states has a value of 2.8; from the calculated spectroscopic quadrupole moment [9] we extracted a quadrupole deformation for a $K = 0$ band of about $\beta = 0.23$. At spin $6\hbar$ the quadrupole moment becomes very small and then it increases toward positive values.

Rotational-like bands have been also identified in ^{46}V, as it will be discussed later in the paper.

4 Band termination

Band termination states correspond to the complete alignment of the valence nucleons to the maximum spin for a given configuration space. Calculations (fig. 3) show that the structure of the states belonging to rotational-like bands in ^{52}Fe, ^{48}Cr and ^{44}Ti is dominated by the $f_{7/2}$ orbital and the band structures terminate with non-collective states involving the $f_{7/2}$ orbital only. The maximum spin that can be built with particles filling only this orbital is $J_{\max} = \frac{1}{2}[n_p(8 - n_p) + n_n(8 - n_n)]$, where n_p is the number of valence protons and n_n is the number of valence neutrons. For all the nuclei we studied in this region, the level schemes were built up to such band termination states and even beyond them. In many of the cases we could extend also the non-natural parity bands up to the band termination in the space defined by the excitation of one particle from the $d_{3/2}$ orbital to the $f_{7/2}$ one ($f_{7/2}^{n_p+n_n+1} d_{3/2}^{-1}$). The structure of the nuclei, toward the band termination and above it, is accompanied by shape changes that can be smooth or abrupt. As a general characteristic of these nuclei it can be noticed that below the band termination the decay strength is concentrated mainly in the yrast structures. Above the band termination, as the configuration space increases, the decay pattern becomes more complicated.

The odd-odd $N = Z$ nucleus ^{46}V, that can be thought as subtracting a proton-neutron pair from the ^{48}Cr core, is the most deformed odd-odd self-conjugate nucleus in the $f_{7/2}$-shell. In this case we identified for the first time the two signatures of a non-natural parity $K^\pi = 0^-$ band up to the terminating state in the $(f_{7/2}^7 d_{3/2}^{-1})$ configuration space. In fig. 4 the level scheme of ^{46}V is shown to illustrate band terminations in both the positive- and negative-parity structures.

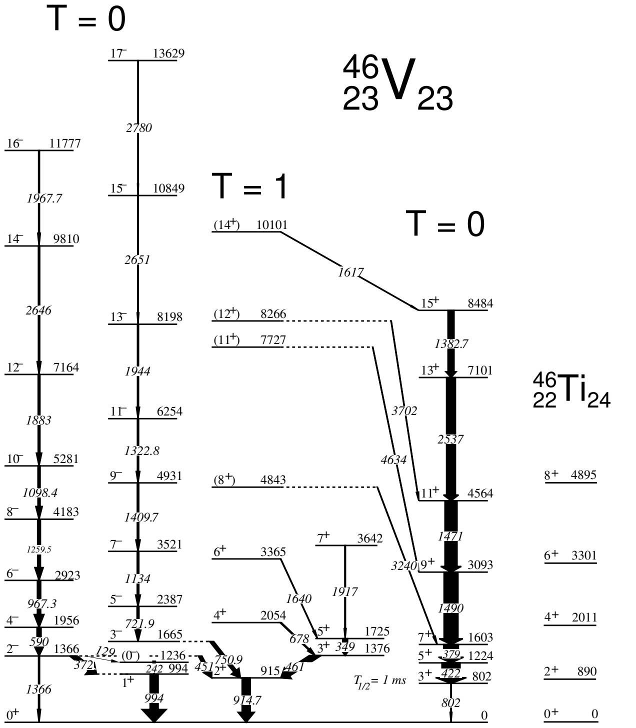

Fig. 4. Level scheme of ^{46}V. On the right side of the picture the lowest states from the ground-state band of ^{46}Ti are illustrated (from ref. [10]).

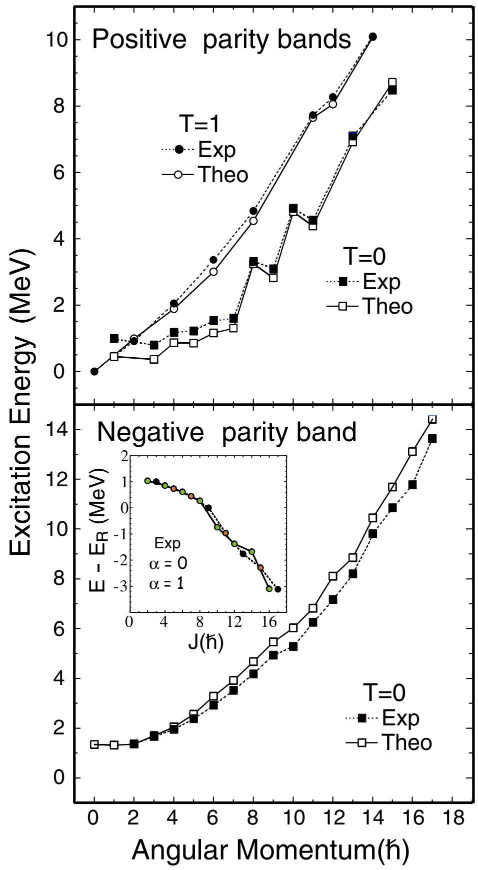

Fig. 5. Excitation energy *versus* angular-momentum plot for the positive-parity $T = 0$ and $T = 1$ bands (upper panel) and for the negative-parity $T = 0$ bands (lower panel). Experimental data are marked with filled symbols and they are compared with shell model calculations. The inset presents the excitation energy of the two signatures of the negative-parity band minus the energy of a rigid rotor (from ref. [10]).

5 Non-natural parity structures and shape coexistence

In the $f_{7/2}$-shell nuclei the intruder bands of non-natural parity are located at low excitation energy. In all $N = Z$ nuclei we identified such structures and, as mentioned in the previous section, we, eventually, extended them up to the band termination.

In ^{48}Cr we solved the controversy on the spin and parity assignment to the intruder band's head [5]. Based on angular distribution and polarization measurements we established that the 1674 keV is a non-stretched $E1$, $\Delta J = 0$ transition establishing the spin and parity of the level at 3532 keV to 4^-. Since in $N = Z$ nuclei the $E1$ transitions between $T = 0$ states are forbidden by the isospin conservation [11] characterizing the 1674 keV gamma-ray transitions allows for an estimate of the isospin mixing in ^{48}Cr. The intruder configurations are explained as being built on $f_{7/2}d^{-1}_{3/2}$ particle-hole excitations. Since such processes imply an increase in the number of degrees of freedom of the nuclear system, in nuclei lighter than ^{48}Cr the intruder structures show a higher degree of collectivity and larger deformations than the yrast bands. In fig. 5 we represented the excitation energy as a function of spin for the bands in ^{46}V. It is evident that the negative-parity bands have a much more regular behavior than the yrast band, consistent with a quadrupole deformation similar to that of ^{48}Cr. Lifetime measurements [12] sustain this shape coexistence at low spins in ^{46}V.

6 The yrast trap in ^{52}Fe

The nucleus ^{52}Fe represented for a long time a challenge to the experimental study of the $f_{7/2}$-shell nuclei. In 1975 [13] an yrast trap at spin $12\hbar$ was reported, and based on simple calculations in the $p_{3/2}f_{7/2}$ space it was argued that the isomeric nature of this state is due to its location below the yrast 10^+ state. However, no experimental evidence was available at the time since only the yrast 2^+ and 4^+ states were known. We have extended the structure of this nucleus [9] up to the 10^+ state confirming the early hypothesis of the inversion of the two yrast states, 10^+ and 12^+. A first hint about the nature of this yrast trap came from the comparison with the cross-conjugate nucleus in the $f_{7/2}$-shell, ^{44}Ti [14]. In fig. 6 the level scheme of ^{52}Fe and the ground-state band of ^{44}Ti are presented. In the pure $f_{7/2}$-shell the spin $12\hbar$ corresponds to the complete alignment of the 6 valence protons and 6 valence neutrons. With so many particles the 12^+ state can be built in different ways and most probably the band termination picture does not hold anymore. Its cross-conjugate partner, the nucleus ^{44}Ti, on the other hand, has only 2 protons and 2 neutrons as valence particles and, as can be seen

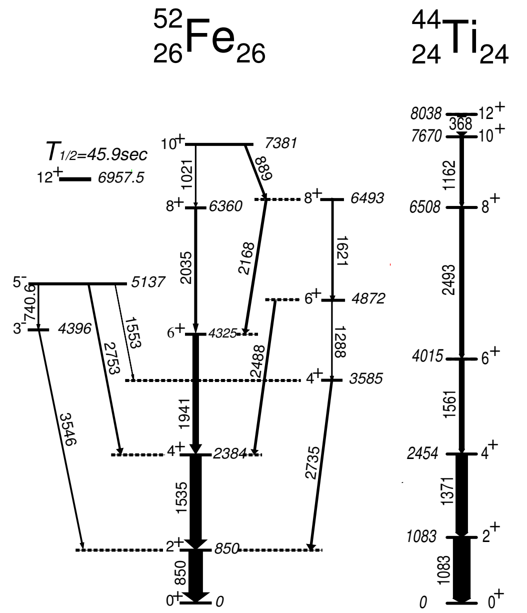

Fig. 6. Level scheme of the $N = Z = 26$ nucleus ^{52}Fe [9]. The exact position of the isomer was taken from ref. [15]. The ground-state band of the $N = Z = 22$ nucleus ^{44}Ti is shown on the right-hand side of the figure.

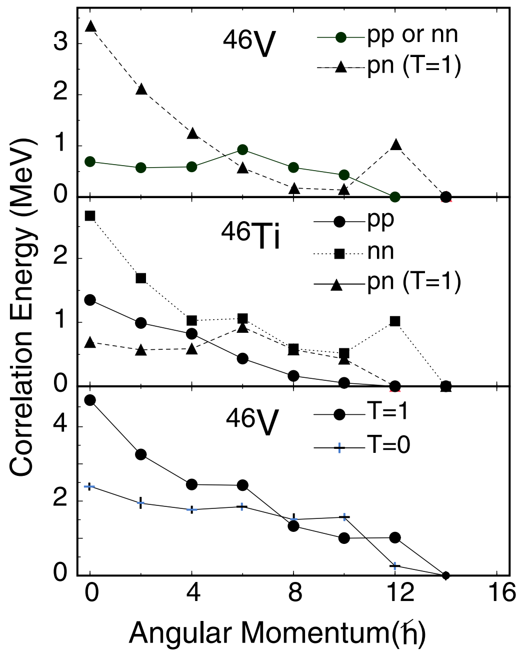

Fig. 7. The pairing correlation energy calculated with the shell model is plotted against the angular momentum for the $T = 1$ isobaric analogue states in ^{46}V and ^{46}Ti. The $T = 1$ pairing channels in ^{46}V (upper panel) and ^{46}Ti (middle panel) are shown. The lower panel illustrates the $T = 1$ and $T = 0$ pairing channels in ^{46}V (from ref. [10]).

from fig. 3, the 12^+ state is a real band termination in the $f_{7/2}$-shell (as the only relevant orbital in its structure is the $f_{7/2}$). In fig. 6, only the relevant part for the discussion of the level scheme of ^{44}Ti is presented. At a first glance, one would say that the structure of the two nuclei is similar but a detailed analysis reveals major discrepancies that demonstrate the importance of the other orbitals from the pf-shell in building the structure of these nuclei and that consequently destroys the cross-conjugate symmetry. If we limit ourselves to the yrast structure that is strongly dominated by the $f_{7/2}$ orbital we can make some qualitative remarks. The structure of the yrast bands looks quite similar except for the 12^+ state that in ^{44}Ti, even if lowered in energy, still remains located above the 10^+ state. In the case of ^{44}Ti the 12^+ state is a real band termination in the pure $f_{7/2}$-shell and according to Faessler [16], in nuclei with few particles (holes) outside closed shells the large spatial overlapping of the associated wave functions lowers the energy of these states which eventually become yrast traps. In ^{44}Ti the 12^+ state is evidently strongly affected being located very close to the yrast 10^+ state. The question is what determined the further lowering of the state in ^{52}Fe. Analyzing the wave functions associated to the states in ^{52}Fe and ^{44}Ti (fig. 3) we noticed that at the band termination in ^{44}Ti and ^{48}Cr the contribution of the other orbitals of the pf-shell goes to zero while in ^{52}Fe it does not. We conclude that this remnant collectivity lowers more the energy of the 12^+ state bringing it below the 10^+ state.

7 Competing T = 0 and T = 1 pn pairing correlations

One of the most important features of the pn pairing is that the proton and the neutron can be coupled both to $T = 0$ and $T = 1$. It was believed that in odd-odd $N = Z$ nuclei the competition between these two coupling modes should appear. This can be illustrated for the most deformed odd-odd $N = Z$ nuclei in the $f_{7/2}$-shell, ^{46}V and ^{50}Mn. The structure of the two nuclei can be imagined as obtained by subtracting or adding, respectively, a proton-neutron pair to the ^{48}Cr core. All the odd-odd $N = Z$ nuclei in the $f_{7/2}$-shell have $J = 0$ $T = 1$ ground states but the $T = 0$ bands have very low excitation energy (below 1 MeV) and become yrast very soon making very difficult to follow the $T = 1$ ground-state bands to high spins. The first case I will discuss is the nucleus ^{46}V [10]. Its level structure was followed up to high excitation energy and the $T = 0$ bands of both positive and non-natural parity were extended up to the band termination states (see fig. 4).

The $T = 1$ band has been identified based on the analogy with the isobaric analogue states in the $N = Z + 2$ nucleus ^{46}Ti [17]. Even if the $T = 0$ proton-neutron interaction $(f_{7/2})^2$ favors the $J = 0$ and $J = 7$ couplings, the strong quadrupole field near the middle of the shell gives rise to a $K^\pi = 3^+$ band head in ^{46}V, corresponding to a proton-neutron pair in the $[301]\frac{3}{2}^-$ Nilsson orbital. According to the charge independence character of the nuclear forces the only difference between the two $T = 0$ isobaric analogue bands in ^{46}V and ^{46}Ti should come from the Coulomb interaction. As shown in fig. 4, up to spin $8\hbar$ the excitation energies of the $T = 1$ states in ^{46}V are larger than those in ^{46}Ti. These Coulomb energy differences can be interpreted in terms of particle alignment [10]. When a

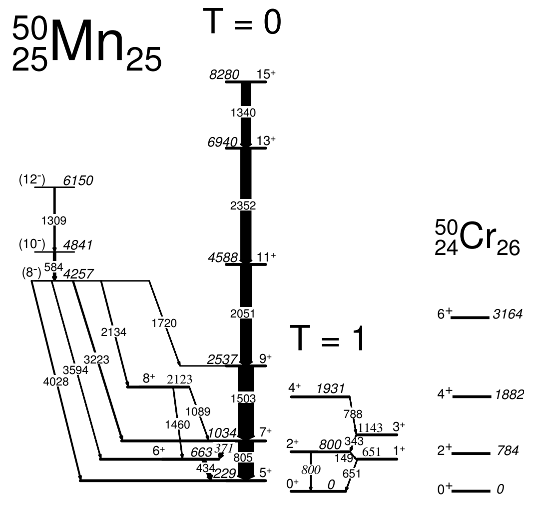

Fig. 8. Level scheme of the $N = Z = 25$ nucleus ^{50}Mn. The $T = 1$ band is compared with the isobaric analogue states in ^{50}Cr.

proton pair is coupled to $J = 0$ the overlap of their wave functions is maximum and so is their Coulomb interaction. By changing the coupling to a different J value the repulsive Coulomb interaction will decrease. At the alignment of neutron or proton-neutron pairs no Coulomb effects are expected. It results that if proton pairs align in ^{46}Ti its level scheme will become more compressed than that of the odd-odd nucleus where a proton-neutron pair aligns. An analysis of these phenomena can be done based on the shell model calculations where the contributions of different types of pairing to the energy of each state were plotted in fig. 7. In the case of ^{46}V the contribution of $T = 1$ pairing terms was plotted. The contribution from the pn pairs is the most important but it decreases with spin. The like-particles pairing stays almost constant. This is consistent with the fact that the first pair to align in the nucleus ^{46}V is a pn pair. In the nucleus ^{46}Ti we have the opposite situation. The contribution from the like-nucleon pairs is more important and it decreases with spin while the pn contribution remains almost constant suggesting that in the nucleus ^{46}Ti we have first the like-particles alignment. The experimentally observed Coulomb energy differences suggest the like-particle alignment in ^{46}Ti and proton-neutron pair alignment in ^{46}V. Full shell model calculations in the pf-shell give a good description of the experimental data. The $T = 1$ ground state and its crossing with the $T = 0$ band at very low excitation energy are very well reproduced. The behavior of the non-natural parity bands is reproduced as well.

A similar situation was found in ^{50}Mn [18] (see fig. 8). In this case again the ground state is a $T = 1$ $J = 0$ state on top of which the isobaric analogue band to the ground-state band of ^{50}Cr was identified. The band head of the $T = 0$ structure has spin/parity 5^+, corresponding to a proton-neutron pair in the Nilsson orbitals $[312]\frac{5}{2}^-$.

8 Conclusions

The recent development in the experimental gamma-ray spectroscopy techniques allowed for a systematic study of the nuclei filling the $f_{7/2}$-shell. The structure of these nuclei is characterized by a large variety of phenomena of collective and single-particle nature. As they allow for both shell model and mean-field calculations, one could get a microscopic understanding of the different phenomena. A special category are the $N = Z$ nuclei. The proton-neutron residual interaction could be tested in both collective and shell models and it was shown that both the isovector and the isoscalar components of the pn pairing are important for establishing the structure of these nuclei. Shell model calculations give a very good description of the energy levels and of the electromagnetic properties for the $N = Z$ nuclei. Mean field calculations help to understand their underlying collective properties.

The results reported in the present paper were obtained from experiments performed by the GASP Collaboration at the XTU Tandem accelerator of the National Laboratories of Legnaro. The shell model calculations with the code ANTOINE [19] were performed by A. Poves, G. Martínez-Pinedo and J. Sánchez-Solano.

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