HIGH SPIN SPECTROSCOPY OF LIGHT $f_{7/2}$ NUCLEI STUDIED WITH EUROBALL IV AND THE RECOIL FILTER DETECTOR: A SMOOTH BAND TERMINATION IN ^{45}Sc*

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New high spin excitations in several light $f_{7/2}$ nuclei have been studied by means of EUROBALL IV. The application of the Recoil Filter Detector has allowed for a significant reduction of the Doppler broadening of measured high energy γ-lines. In the article, a band termination observed for the intruder rotational bands in ^{45}Sc is discussed. Results are compared with shell model calculations.

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1. Introduction

Although $f_{7/2}$ shell nuclei lie close to the doubly magic systems ^{40}Ca and ^{56}Ni, several of their properties such as band-like structures and strong inband E2 transition rates can be viewed as a sign of collectivity.

In the middle of the $f_{7/2}$ shell, the number of active particles and the configuration space available are big enough to allow for the collective motion of nucleons. In fact, the experimental results obtained for nuclei in the vicinity of ^{48}Cr [1] have pointed out to the important role played by a collective excitation in building up levels with high angular momentum. Collective behaviour was also identified in lighter odd-A $f_{7/2}$ nuclei where a particle-hole excitation across the closed shell takes place. Our previous studies [2] of ^{45}Sc, ^{45}Ti and ^{43}Ca have revealed that in these nuclei unnatural parity levels constitute regular rotational bands with almost constant quadrupole moment corresponding to a prolate deformation with $\beta \approx 0.3$.

The $f_{7/2}$ orbit is rather well-separated from the other shells. Therefore, experimental observation of pure single-particle configurations giving a contribution to high spin states is feasible in this region. Such configurations can be exactly accounted for by shell model calculations. In fact, it turns out that many features in $f_{7/2}$ nuclei at high spin can be well-explained by this theory if only the $f_{7/2}$ shell is taken into account [3]. However, a natural spin limitation in the shell model comes from the fact that the angular momentum increases only by the alignment of valence nucleons within the available configuration space. The maximum spin $I_{\max}$ is obtained when all valence nucleons are fully aligned. In the $f_{7/2}$ nuclei states with angular momentum larger than $I_{\max} = 1/2[(Z-20)(28-Z)+(N-20)(28-N)]$ result from excitation to higher pf shells.

Further investigation of levels beyond the $f_{7/2}$ shell limit in $f_{7/2}$ nuclei should throw more light on the origin of nuclear rotation. Whether or not the collective behaviour initiated below the maximum aligned spin will continue above $I_{\max}$, or whether a drastic change in a single-particle configuration will cause the rotational bands to terminate, are still intriguing questions.

So far, very little is known about the structure of the $f_{7/2}$ nuclei above the maximum aligned spin. In some nuclei rotational bands have been observed up to this limit, but only in a few cases has a band termination been reported [4, 5]. The main experimental difficulty in studying high spin excitation in light systems is the extensive Doppler broadening of measured γ-ray lines. This is due to first the high energy of the γ-transitions, and second the high velocity and spatial spread of the recoils, since the light mass nuclei have to be produced in fusion-evaporation reactions induced by energetic heavy ions.

Owing to the excellent performance of our Recoil Filter Detector (RFD) [6] which measures precisely the recoil velocity vector for every event, we can reduce the Doppler broadening of γ-ray lines. This allows measuring efficiently high energy γ-transitions when using a powerful germanium detector array, such as EUROBALL IV [7].

In the present work we report on our attempt to extend the knowledge of excitations in several $f_{7/2}$ nuclei much beyond the $f_{7/2}$ shell limit.

2. Experiment

The experiment was performed at the IReS in Strasbourg. A pulsed beam of 68 MeV ^{18}O ions bombarded a metallic ^{30}Si target of 800 μg/cm^2 [8]. Gamma-rays were detected by the EUROBALL IV array consisting of high efficiency cluster and clover detectors. The RFD incorporating 18 heavy ion detectors was placed at a distance of 134 cm behind the target. To facilitate the mounting the tapered detectors of EUROBALL were removed.

The RFD measured a direction and time-of-flight (TOF) of recoils with respect to the beam axis, and a beam pulse signal in coincidence with γ-rays. An efficiency of the RFD for the reaction used and the geometry of the present set-up is illustrated in Fig. 1. The calculated efficiency agrees well with the measured value which is of the order of 40%.

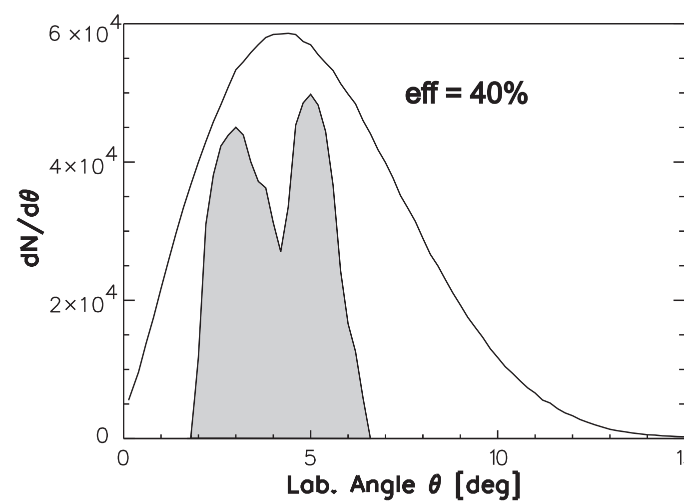

Fig. 1. Calculated angular distribution of ^{45}Sc recoils emitted in the ^{30}Si(^{18}O, $p2n$) reaction at 68 MeV for the 800 μg/cm^2 target. The shaded area corresponds to the fraction of recoils detected by the RFD. The estimated efficiency is equal to 40%.

The recoil velocity vector determination for each event has improved the measured γ-spectra. Fig. 2 shows a part of a γ-spectrum measured by a single germanium crystal. A considerable reduction of the γ-line width is clearly seen in the lower spectrum. The FWHM of γ-line at ~ 1.5 MeV is only 4.5 keV.

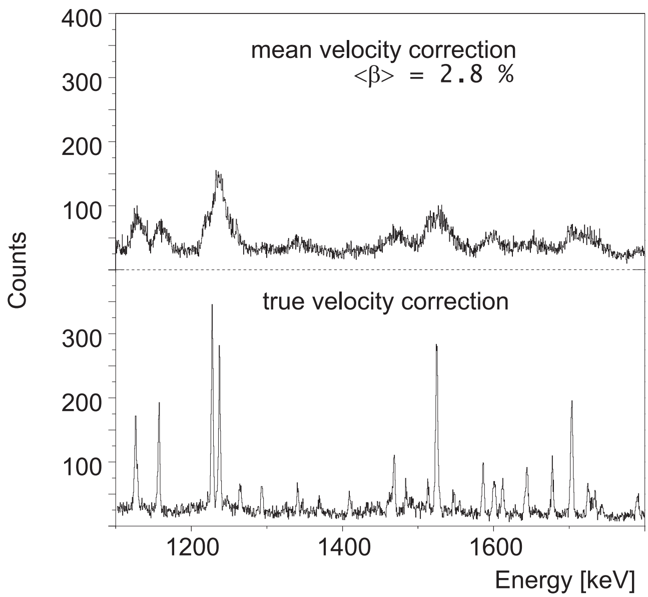

Fig. 2. A part of a γ-spectrum measured by a single germanium crystal of a cluster detector with the correction for the mean recoil velocity (upper part) and for the measured velocity vector of every recoil (lower part).

The TOF spectra of recoils produced in the $p2n$, $\alpha 2n$ and $2\alpha 1n$ evaporation reaction channels as well as the total projection are presented in Fig. 3. The selection of different recoils was done by gating on the known γ-transitions. Due to relatively thick target, the velocity distribution of recoils and consequently their time of flight distribution is broad. As one can see from Fig. 3, there is a significant difference in the shapes of TOF spectra when either a proton or an alpha-particle emission takes place. Even though, as illustrated in Fig. 4, γ-line widths are similar for different residual nuclei in the wide energy range. Moreover, there is also a visible difference in the positions of those spectra in the time scale that makes possible — to some extent — a selection of exit channel.

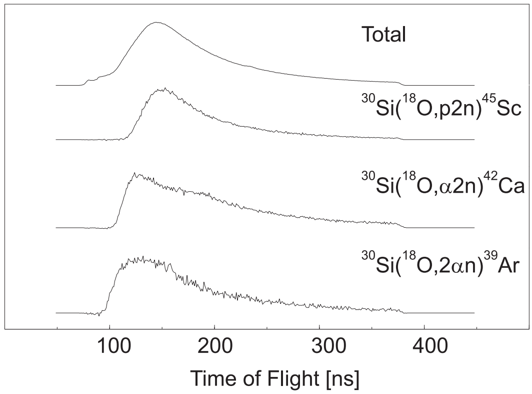

Fig. 3. Time-of-flight spectra measured by the RFD for different fusion-evaporation reaction products (see text for discussion).

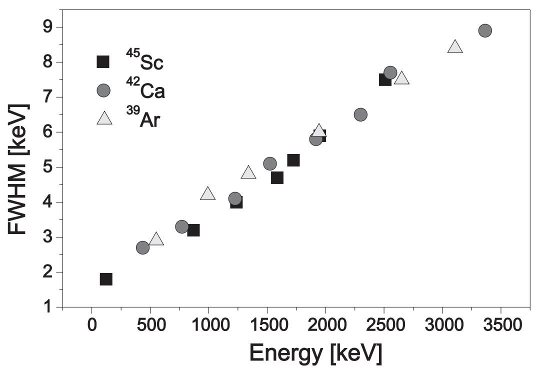

Fig. 4. FWHM of γ-lines versus γ-ray energy for different residual nuclei produced in the reactions given in Fig. 3. Gamma-line widths were corrected for the Doppler effect using the RFD.

3. Results

The experiment has provided high quality data on several new high spin excitations in ^{38,39}Ar, ^{41,42}K, ^{41,42,43,44,45}Ca, ^{44,45}Sc and ^{43,45}Ti. In the ^{45}Sc nucleus we have identified over 40 new γ-transitions deexciting mainly high spin levels. The γ-ray energies range from several hundred keV to almost 6 MeV. Double and triple γ-ray coincidences were used to establish the decay pattern of ^{45}Sc. Analysis of DCO ratios and linear polarisation has given spin and parity assignments for the major part of the identified levels. Since the data is still being analysed, we will discuss here only the case of a band termination in ^{45}Sc. Different aspects concerning this and other nuclei will be reported in forthcoming articles.

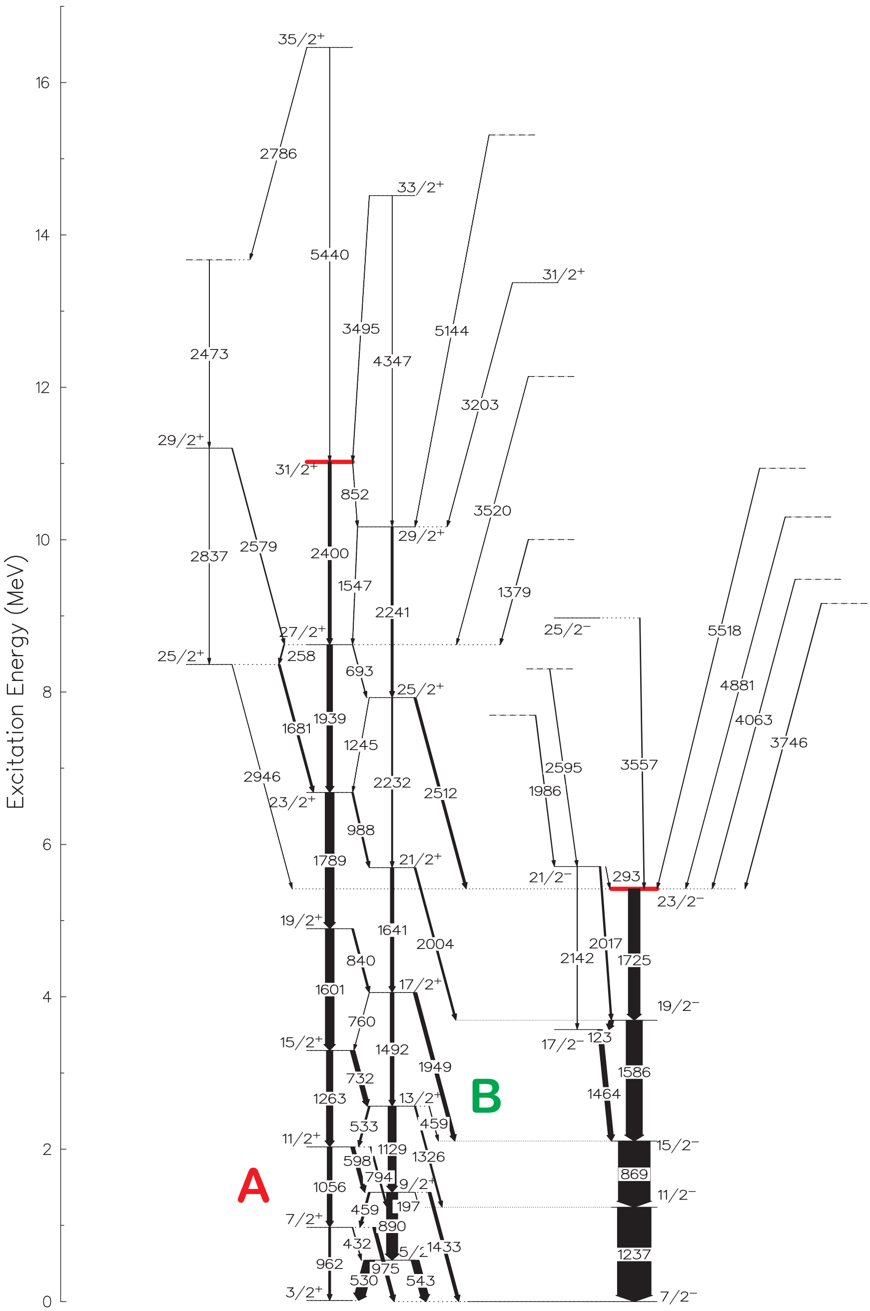

Fig. 5. Partial level scheme of ^{45}Sc derived from the present work. A and B denote the two rotational signature-partner positive parity bands.

The partial level scheme of ^{45}Sc is shown in Fig. 5. The negative parity yrast band results from an excitation within the $f^5_{7/2}$ configuration [2]. Gamma-rays deexciting these levels constitute the main decay path in the ^{45}Sc nucleus. The yrast structure extends up to maximum available spin of $23/2\ \hbar$ but several transitions feeding the maximum spin level have also been observed.

The positive parity levels form two rotational signature-partner bands "A" and "B" [2]. They are based on a $d_{3/2}$ proton particle–hole excitation coupled to the $f^6_{7/2}$ configuration. The positive parity bands conserve their regular behaviour up to a level at maximum aligned spin $31/2\ \hbar$ which turns out to be the band terminating state. Several γ-transitions of 3–5.5 MeV feeding the highest-lying levels have been observed. More detailed rotational features of the bands A and B can be seen when plotting the excitation energy relative to the rotational energy of a rigid body as a function of the angular momentum. Such a plot is shown in Fig. 6. Both signature-partner bands exhibit similar behaviour. At low spin, the excited state energies are close to the reference rotor values, whereas at higher angular momenta they gradually lose collectivity. However, above the maximum aligned spin this smooth trend is not continued, a fact which may be associated with an abrupt change of a single particle configuration.

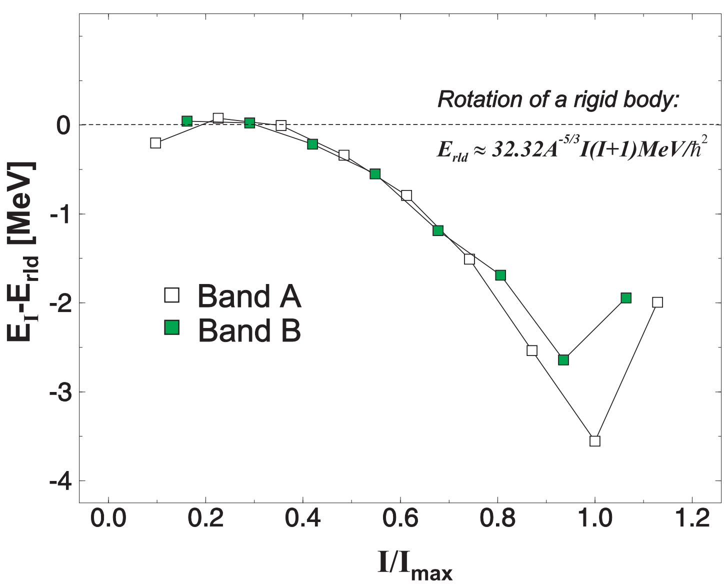

Fig. 6. A plot of the E_I-$E_{\rm rld}$ differences as a function of spin I for positive parity bands A and B (conf. Fig. 5). E_I — experimental energy of a state with a spin I, $E_{\rm rld}$ — rigid rotor energy of this state calculated according to the formula given in the figure.

As mentioned above, shell model calculations in many cases reproduce well the observed properties of highly excited $f_{7/2}$ nuclei. However, an extension of the $f_{7/2}$ space is often necessary. In Fig. 7 we have compared our results for the positive parity levels in ^{45}Sc with recent shell model calculations performed in a full pf configuration space [9]. One sees very good agreement between the experiment and the calculations over the whole range of spins. The calculation accounts well for the large energy gap above the $I_{\rm max} = 31/2\ \hbar$. Moreover, the theory predicts that beyond the maximum spin limit collective-like behaviour disappears. This seems to be in accord with the experimental observation of the $I = 33/2\ \hbar$ state decay where the M1 transition is twice as strong as the competing E2 radiation.

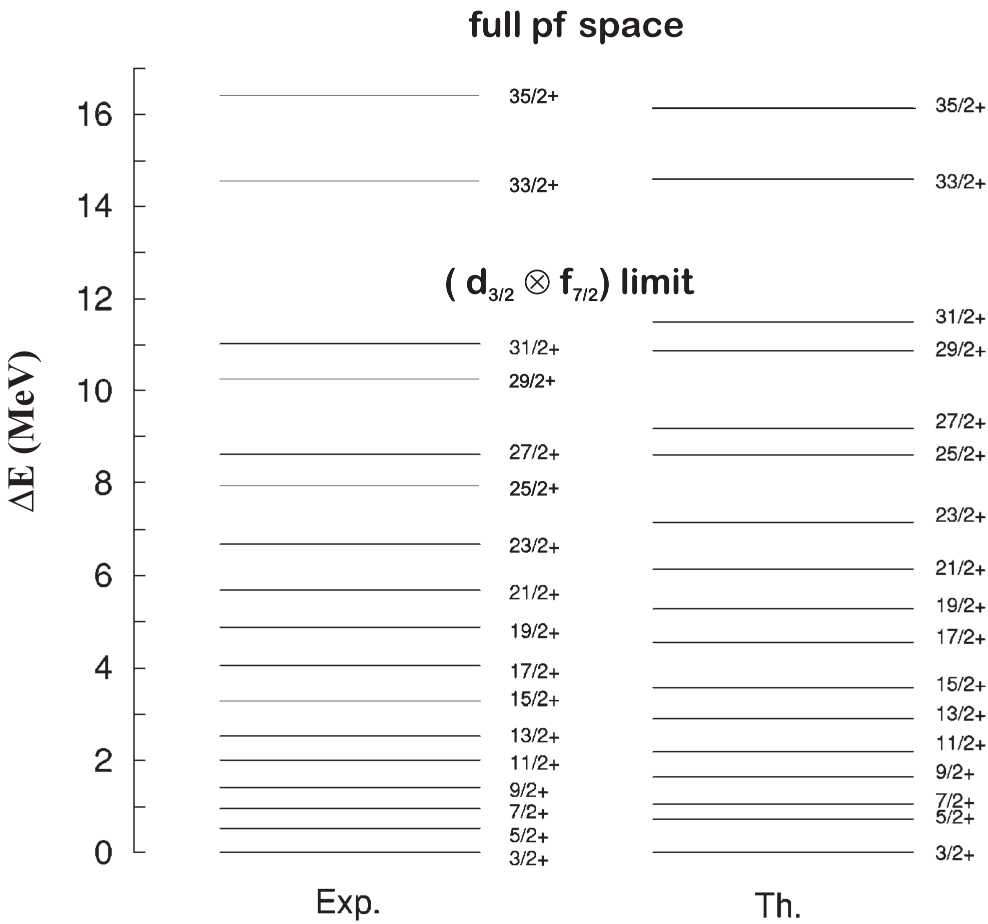

Fig. 7. The comparison of the experimental and calculated [9] excitation energies of the positive parity states in ^{45}Sc.

4. Conclusion

In the present work we have observed a smooth band termination in the ^{45}Sc nucleus. The investigated positive parity bands exhibit rather regular rotational behaviour up to the maximum aligned spin of $31/2\ \hbar$ available for the $d^{-1}_{3/2} f^{6}_{7/2}$ configuration. Comparison with the shell model calculations suggests that the macroscopic rotation of the nucleus in that model can be generated by the coupling of several single-particle configurations within this space. However, an admixture of higher lying pf orbitals causes the collective motion to fail.

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