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Letter

Unnatural-parity states in $^{44}_{21}Sc_{23}$

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Abstract. High-spin states of the ^{44}Sc nucleus, populated in the 68 MeV ^{18}O + ^{30}Si reaction, have been studied in a γ-γ-recoil coincidence experiment. The detailed decay pattern, with various paths and cross-transitions, has been extended up to 9.1 MeV. High-quality DCO and polarization information assign spins and parities for the majority of the observed levels. The negative-parity states are discussed and compared with rotational bands in neighbouring $f_{7/2}$-shell nuclei.

PACS. 21.60.Cs Shell model – 23.20.Lv γ transitions and level energies – 27.40.+z $39 \leq A \leq 58$

The phenomenon of shape coexistence in the $f_{7/2}$-shell nuclei was discovered and studied in the odd-A isotopes in the 1970s. The early γ-spectroscopy investigations revealed that in those nuclei, beside yrast excitations expected for a spherical shape, one could observe a sequence of a few regularly spaced low-lying levels characteristic of nuclear deformation. Collective properties of those unnatural-parity states have been proven by the measured enhancements of the $E2$ transition probabilities determining the deformation parameters ranging from $\beta = 0.26$ for ^{43}Sc up to $\beta = 0.36$ for ^{47}V [1].

According to the shell-model description, formation of collective structures in the $f_{7/2}$ nuclei (having a relatively small number of valence nucleons) requires additional excitations of the core. A band of unnatural-parity states arises when one of the core particles participates in the collective cross-shell excitations. This band can terminate in the state with the maximum aligned spin for the coupling of the particle-hole excitations to the available angular momentum for the valence nucleons.

Recently, very regular rotational bands of unnatural-parity states have been identified in many odd-A nuclei. In two cases, *i.e.* in the ^{45}Sc [2] and ^{47}V [3] nuclei, the positive-parity bands have been extended up to the band-terminating states at spins $I^\pi = 31/2^+$ and $I^\pi = 35/2^+$, respectively.

In the even-even $f_{7/2}$-shell nuclei, the unnatural-parity states lie much higher in excitation energy and their rotational behaviour is less pronounced. The rotational-like band of negative-parity states up to the $I^\pi = 13^-$ at 10.6 MeV has been observed in ^{44}Ca [4], while the band-terminating state with spin $I^\pi = 17^-$ has been identified in ^{46}Ti [5] at 15.5 MeV.

The odd-odd nuclei have long been known to exhibit much complicated structure. Until now, the experimental information on the high-spin structures in the odd-odd $f_{7/2}$ nuclei is limited to the two extensively studied $N = Z$ nuclei: ^{46}V [6,7] and ^{50}Mn [8], and to the recently investigated ^{48}V [9]. As shown in the two vanadium isotopes, the observed excitations form very intricate level patterns for the natural- as well as for the unnatural-parity sequencies. In both cases, the negative-parity states have been extended up to the $I^\pi = 17^-$ state interpreted as band termination.

In this work, we present results of our study of high-spin excitations in the odd-odd ^{44}Sc nucleus. The data come from an in-beam experiment performed with the VIVITRON accelerator at IReS in Strasbourg. The ^{44}Sc nuclei were populated in the (^{18}O, $p3n$) reaction with a

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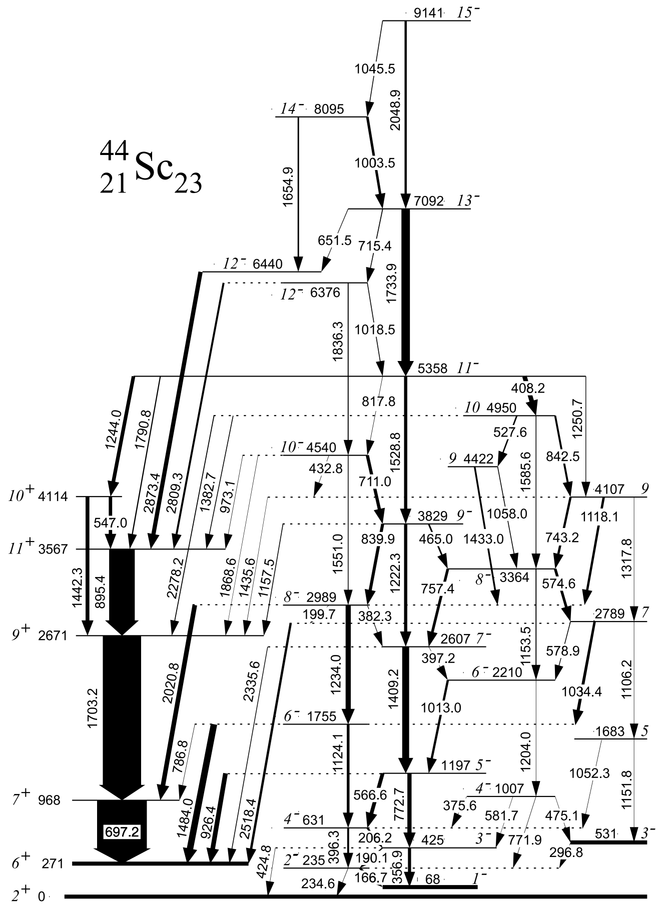

Fig. 1. Partial level scheme of the ^{44}Sc nucleus as deduced from our experiment. For clarity, we do not include the 4^+ state at 350 keV also observed in the present work.

pulsed beam of 68 MeV ^{18}O ions bombarding a metallic, 800 μg/cm^2 thick ^{30}Si target [10]. The experimental set-up contained the high-efficiency EUROBALL IV germanium-detector array in coincidence with the Recoil Filter Detector (RFD) [11]. Here, the RFD was exploited to reduce large Doppler broadening of the observed γ lines, which was caused by high recoil velocity ($v/c = 2.8\%$) [2]. A thorough analysis of γ-γ- and γ-γ-γ-recoil coincidences, together with DCO ratios and γ-polarization information, provided the high-spin level scheme of the ^{44}Sc nucleus. An essential part of it is presented in fig. 1 and experimental results for new levels identified in negative-parity band are collected in table 1.

Until now, the available information on the high-spin structure of the ^{44}Sc nucleus was rather scarce and came primarily from the investigation of ref. [12]. A cascade of the 697.2, 1703.2, 895.4 and 547.0 keV γ-transitions, identified above the $I^\pi = 6^+$ isomer, fixed the yrast positive-parity levels up to the state at 4114 keV. The uncertain placement of the weak 408.2 keV γ-ray above the $I^\pi = 11^+$ level located an additional state at 3975 keV. Properties of low-lying states have also been studied in other experiments [13,14] and, consequently, a sequence of negative-parity levels was established up to the $I^\pi = 5^-$ state at 1197 keV.

Table 1. The properties of new levels in negative-parity band observed in ^{44}Sc. Level energies E_i, γ-ray energies E_γ, branching ratios $B.R.$, DCO ratios and multipole assignments of transitions are listed.

E_i (keV)	E_γ (keV)	$B.R.$	R_{DCO}	$I_i \to I_f$
1755.0	786.8$^{(a)}$	3(1)	1.08(20)$^{(b)}$	$6^- \to 7^+$
	1124.1(2)	31(4)	1.06(26)	$6^- \to 4^-$
	1484.0(1)	100(3)	1.04(9)	$6^- \to 6^+$
2606.7	396.2$^{(a)}$	7(2)	1.58(23)	$7^- \to 6^-$
	1409.2(1)	100(3)	1.01(8)	$7^- \to 5^-$
	2335.6(3)	11(2)	1.04(18)$^{(b)}$	$7^- \to 6^+$
2989.0	199.7(2)	5(1)		$8^- \to 7$
	382.3$^{(a)}$	13(3)		$8^- \to 7^-$
	1234.0(2)	100(3)	0.97(17)	$8^- \to 6^-$
	2020.8(1)	86(7)	1.07(10)$^{(b)}$	$8^- \to 7^+$
3829.0	465.0(1)	45(6)	1.88(20)	$9^- \to 8^-$
	839.9(3)	80(8)		$9^- \to 8^-$
	1039.7(2)	14 (4)		$9^- \to 7$
	1157.5(3)	40(8)	1.07(11)	$9^- \to 9^+$
	1222.3(1)	100(9)	1.03(7)	$9^- \to 7^-$
4540.0	432.8$^{(a)}$	12(3)		$10^- \to 9$
	711.9(2)	100(8)	1.69(26)	$10^- \to 9^-$
	973.1(3)	12(3)	1.70(25)	$10^- \to 11^+$
	1551.0$^{(a)}$	14(4)		$10^- \to 8^-$
	1868.6(3)	16(3)		$10^- \to 9^+$
5357.8	408.2(1)	100(3)	1.85(12)	$11^- \to 10$
	817.8(3)	10(2)		$11^- \to 10^-$
	1244.0(2)	80(5)	1.64(15)	$11^- \to 10^+$
	1250.7(3)	16(2)	1.11(17)	$11^- \to 9$
	1528.8(2)	73(5)	1.04(15)	$11^- \to 9^-$
	1790.8(2)	27(3)	1.08(11)	$11^- \to 11^+$
6376.3	1018.5(3)	28(5)		$12^- \to 11^-$
	1836.3(3)	38(5)		$12^- \to 10^-$
	2809.3(4)	100(6)	1.83(18)	$12^- \to 11^+$
6440.2	2873.4(4)	100(5)	1.56(19)	$12^- \to 11^+$
7091.7	651.5(2)	4(1)	1.94(22)	$13^- \to 12^-$
	715.4(2)	7(1)	2.04(32)	$13^- \to 12^-$
	1733.9(2)	100(6)	0.99(7)	$13^- \to 11^-$
8095.1	1003.5(3)	100(8)	1.74(24)	$14^- \to 13^-$
	1654.9(2)	87(10)	1.07(15)	$14^- \to 12^-$
9140.6	1045.5(3)	27(6)	1.86(32)	$15^- \to 14^-$
	2048.9(3)	100(9)	1.01(15)	$15^- \to 13^-$

(^{a}) γ-ray energy as an energy difference between initial and final level extracted in case of a weak transition or a doublet.
(^{b}) DCO ratio from the spectra gated on the $\Delta I = 1$ transition. The value $R_{DCO} \approx 1$ indicates here $\Delta I = 1$ character for the respective transition.

High statistics collected in our experiment and an excellent quality of measured spectra extend the knowledge on ^{44}Sc high-spin structure. In fig. 2, we present two examples of the γ-γ-recoil coincidence spectra selected to demonstrate a new placement of the 408.2 keV transition. The upper part of fig. 2, *i.e.* the coincidence spectrum with the gate on the 1703.2 keV γ-ray, highlights γ-transitions

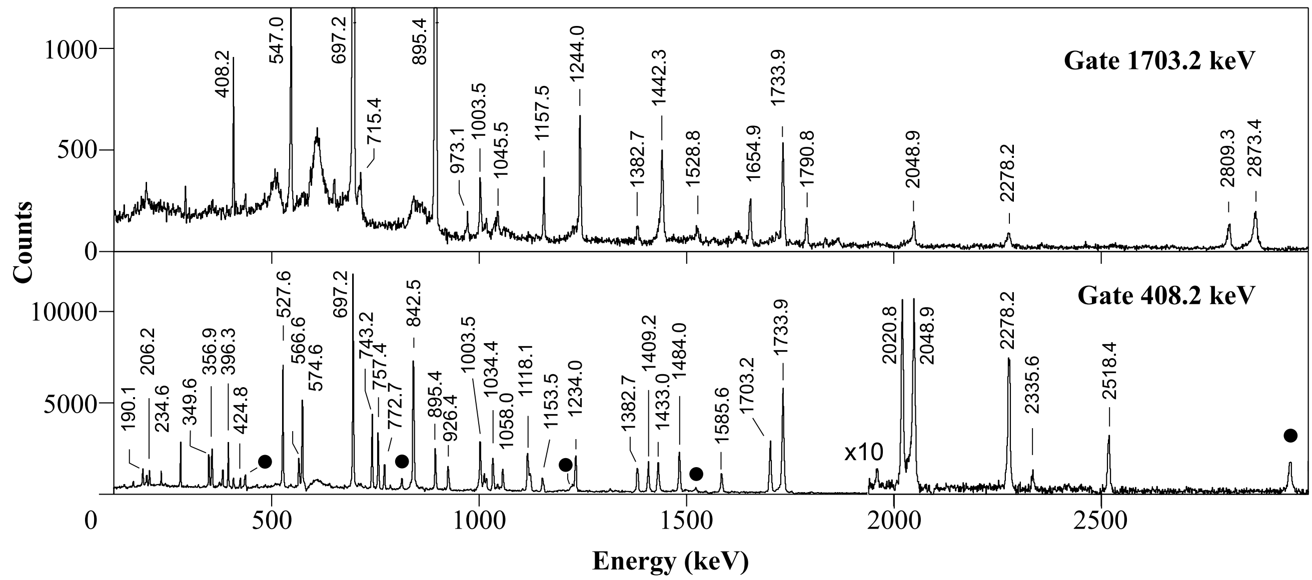

Fig. 2. Doppler-corrected γ-γ-recoil coincidence spectra selected to document the location of the $I^\pi = 11^-$ state at 5358 keV in the ^{44}Sc nucleus. Lines marked with the filled circles in the lower spectrum come from coincidence with the 409.1 keV γ-ray in ^{42}Ca which is not fully resolved from the gating transition.

in the high-spin de-excitations to the yrast band. Notice, only four of the γ-rays present in this spectrum were known from the previous studies. From the spectrum in the lower part of fig. 2, it is evident that the 408.2 keV transition coincides not only with the γ-rays of the yrast cascade, but also with the γ-transitions belonging to the decay of negative-parity states. These and all other coincidence relations indicate strongly that the 408.2 keV γ-ray depopulates the level at 5358 keV and thus lies much higher in energy than proposed before [12]. The detailed analyses of many γ-γ-recoil coincidences establish the level scheme of the ^{44}Sc nucleus up to the 9141 keV excitation and show the high complexity of its decay.

The spin assignments are based mainly on DCO information. Events from detectors of chosen geometry were sorted into appropriate γ-γ-recoil matrices. The experimental DCO factors were extracted from the coincidence spectra gated on known $E2$ transitions. In some cases, the DCO ratios were obtained from the spectra gated on the $\Delta I = 1$ transition. The detailed analysis of the DCO ratios and the fact that depopulation of each state branches into several decay paths eliminated some of the spin values and uniquely determined the spin for almost all observed levels. Polarisation measured for several intense γ-transitons fixed level parities up to the $I^\pi = 13^-$ state at 7092 keV. For the two highest-lying states, at 8095 and 9141 keV, we suggest negative parity. It would be hard to understand a parity change for those levels, whereas with negative-parity assignments they complete the unnatural-parity band up to the $I^\pi = 15^-$ level.

In the shell-model description, the ^{44}Sc nucleus has one proton and three neutrons occupying the $f_{7/2}$ orbital outside the ^{40}Ca core. Thus, the yrast positive-parity levels, shown to the left in fig. 1, represent highest-spin excitations of the multiplet formed by a coupling of these valence

Table 2. The experimental values of lifetime τ for states above 6 MeV obtained with the method of ref. [15], with respective experimental $B(E2)_{\text{exp}}$ transition rates.

E_{i} (keV)	I_{i}	τ (fs)	E_γ (keV)	$B(E2)_{\text{exp}}$ (e^2fm^4)
6376.3	12^-	450(150)	1836.3(3)	20(8)
6440.2	12^-	115(35)	1900.2$^{(\text{a})}$	< 28
7091.7	13^-	282(100)	1733.9(2)	166(60)
8095.1	14^-	256(80)	1654.9(2)	119(42)
9140.6	15^-	170(30)	2048.9(3)	105(30)

($^{\text{a}}$) Unobserved γ-transition, its branching ratio estimated as less than 10% of the γ-intensity depopulating this level.

particles in the $f_{7/2}$-shell up to the level at 3567 keV with maximum spin $I^\pi = 11^+$. The higher-lying 4114 keV level with spin and parity, $I^\pi = 10^+$, uniquely assigned from our results, can be interpreted as a member of the same $(\pi f_{7/2} \nu f^3_{7/2})$ multiplet. The negative-parity states up to the $I^\pi = 15^-$ level at 9141 keV, shown in the middle of fig. 1, can be understood as a coupling of the valence nucleons to the lowest $d_{3/2}$-$f_{7/2}$ particle-hole excitations of the ^{40}Ca core. The 9141 keV state with spin $I^\pi = 15^-$, which is the maximum aligned spin for the $(\pi d^{-1}_{3/2} f^2_{7/2} \nu f^3_{7/2})$ configuration, can be treated as a band-terminating state. The band termination at that level is supported by the $B(E2)_{\text{exp}}$ transition probability calculated from the measured lifetime. As is seen in table 2, levels seem to lose their collectivity with increasing spin. It is a characteristic feature when approching the band-terminating state. Notice the different properties of the two $I^\pi = 12^-$ levels. The small values of $B(E2)_{\text{exp}}$ transition rate and the

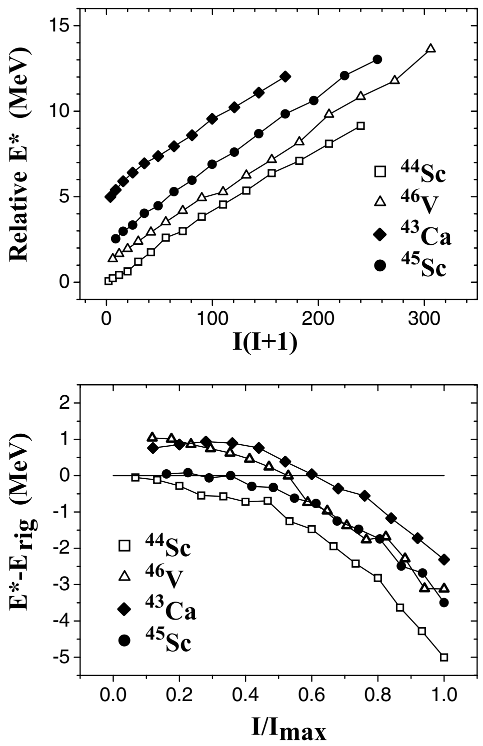

Fig. 3. Excitation energies E^* of unnatural-parity levels in ^{44}Sc, ^{46}V [7], ^{43}Ca and ^{45}Sc [2] shown *vs.* $I(I+1)$ (upper panel; for clarity the plots are shifted in energy by an arbitrary value) and compared to a rigid-rotor energy $E_{\rm rig}$ (lower panel).

decay modes, mainly to the yrast $I^\pi = 11^+$ state, suggest severe alteration in their structure.

The properties of the negative-parity states in ^{44}Sc can be compared with neighbouring nuclei in which the rotational character of the unnatural-parity sequencies is well documented by experiment and theory. For such comparison, we select two other $N = 23$ isotones, odd-odd ^{46}V [7] and odd ^{43}Ca, as well as the heavier ^{45}Sc [2] isotope. In the upper part of fig. 3, the relative excitation energies are plotted as a function of angular momentum $I(I+1)$. The lower part of fig. 3 presents excitation energies relative to a rigid-rotor energy, $E_{\rm rig} = 32.32A^{-5/3}I(I+1)$, as a function of $I/I_{\rm max}$, where $I_{\rm max}$ denotes the spin of the respective band-terminating state. The negative-parity levels in ^{44}Sc show the same regularities as unnatural-parity bands observed in the three other nuclei.

In summary, we have observed the complicated structure of the ^{44}Sc nucleus. The coupling of valence nucleons in the $f_{7/2}$-shell forms the yrast positive-parity sequence in which our work removes some unambiguities at the highest excitations. The 408 keV γ-transition is placed to deexcite the negative-parity $I^\pi = 11^-$ state at 5358 keV. The negative-parity states are extended up to the 9141 keV excitation with suggested spin $I^\pi = 15^-$. This sequence exhibits the common features of the deformed unnatural-parity bands identified in neighbouring nuclei. Its character is described by the additional $d_{3/2}$-$f_{7/2}$ particle-hole core excitations with the maximum aligned spin $I^\pi = 15^-$ for ^{44}Sc constituting the band-terminating state.

The very recent shell-model study of collective intruder structures, and fully aligned high-spin states, in the lighter $f_{7/2}$-shell nuclei with the *sdfp*-configuration space provide a description of the ^{44}Sc structure [16]. According to these calculations, the lower-spin states as well as the $I^\pi = 15^-$ band-terminating state are dominated by proton particle-hole excitations, and the intermediate-spin states between $I^\pi = 8^-$ and $I^\pi = 13^-$ are characterized by almost equal mixtures of proton and neutron core excitations. The calculated energies of the negative-parity intruder states are in a good agreement with experimental values, whereas the measured $B(E2)_{\rm exp}$ transition probabilities for high-spin states are much above the calculated values showing their more collective nature. The presented calculations were limited to 1p-1h excitations and further studies including 3p-3h cross-shell excitations are in progress.

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