Vol. 49 (2018) *ACTA PHYSICA POLONICA B* No 3

ELECTROMAGNETIC PROPERTIES OF ^{45}Sc STUDIED BY LOW-ENERGY COULOMB EXCITATION*

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(Received February 6, 2018)

A Coulomb excitation experiment to study electromagnetic properties of ^{45}Sc was performed at the Heavy Ion Laboratory, University of Warsaw, using a 70 MeV ^{32}S beam. Measured γ-ray intensities together with existing spectroscopic data were used to extract a set of matrix elements between the populated states. Upper limit on $B(\mathrm{E3};7/2^- \to 5/2^+)$ is given.

DOI:10.5506/APhysPolB.49.567

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[*] Presented at the XXXV Mazurian Lakes Conference on Physics, Piaski, Poland, September 3–9, 2017.

1. Introduction

^{45}Sc is an odd–even stable nucleus lying in the vicinity of the doubly magic ^{40}Ca. For many years, this mass region has been a subject of numerous theoretical and experimental studies. They demonstrated that the properties of the ground-state band can be well-described by the spherical shell model, while particle–hole excitations across the doubly-magic shell gap result in appearance of the superdeformed structure as it was first reported in ^{40}Ca [1], and further investigated via the Coulomb excitation in ^{42}Ca [2].

The ^{45}Sc nucleus has one additional proton and 4 neutrons beyond the $Z = N = 20$ shell closure. The number of active particles and the $p_{3/2}f_{7/2}$ configuration space are large enough to allow for the collective motion of nucleons. The negative-parity states built on the $7/2^-$ ground state have a spherical character, while a well-deformed rotational-like band is formed upon the $I^\pi = 3/2^+$, 12.4 keV intruder level in ^{45}Sc [3–6]. Origin of such excited states can be explained in the framework of the Nilsson model: the Nilsson orbitals of the $1d_{3/2}$ shell [2,0,2]3/2 and [2,0,0]1/2 and the lowest orbitals of the $1f_{7/2}$ shell [3,3,0]1/2 and [3,2,1]3/2 approach each other when the deformation increases, thereby producing a core-excited state nearly degenerated with the spherical ground state [7]. The $I^\pi = 3/2^+$ isomer in ^{45}Sc lives long enough ($T_{1/2} = 318$ ms) to be investigated using the collinear laser spectroscopy. Such measurements [3] showed the difference in the charge radii between the ground and isomeric states of ^{45}Sc. The electric quadrupole moment for the isomeric state was obtained to have a positive sign and the value of $Q_{\rm s} = 0.28(5)$ b. This result corresponds to a prolate deformation with the elongation parameter $\beta \sim 0.3$, whereas the results for the ground state pointed to its spherical shape.

The high-spin states in ^{45}Sc were studied in the ^{18}O + ^{30}Si fusion–evaporation reaction at 68 MeV beam energy [4, 5]. The nuclei of interest were populated in the $p2n$ evaporation channel, and the lifetimes of the states in the intruder band were determined starting from the $11/2^+$ state at 2031.2 keV up to the maximum-aligned state at $31/2^+$. From the extracted lifetime of the $11/2^+$ state ($\tau = 1.4(2)$ ps), assuming the rotational model and a prolate deformation, the intrinsic quadrupole moment for this state is $Q_0 \sim 1$ b, and the corresponding spectroscopic quadrupole moment is $Q_{\rm s} \sim 0.4$ b. This work allowed to extract the deformation parameter $\beta \sim 0.3$, rather constant along the intruder band in ^{45}Sc, and consistent with the above-mentioned findings for the band head at low excitation energy [3].

For a complete picture of the deformation and shape evolution along this intruder band, a measurement of the quadrupole moment of the $7/2^+$ state at 974.4 keV is essential. Additionally, information on the quadrupole properties in ^{45}Sc, such as signs and magnitudes of quadrupole moments, as well as the transitional electromagnetic matrix elements between low-lying states (*e.g.* $5/2^+$ state at 543 keV), will contribute towards a better understanding of the role played by single-particle degrees of freedom in creating nuclear collectivity. The low-energy Coulomb excitation can provide valuable new information on the low-lying states in ^{45}Sc, being the only experimental technique that can distinguish between prolate and oblate shapes of the nucleus in a short-lived excited state.

2. Experimental details

The Coulomb-excitation measurement to study ^{45}Sc was performed in November 2016 at the Heavy Ion Laboratory, University of Warsaw. A ^{32}S beam of 70 MeV energy, delivered by the U-200P cyclotron, impinged on a thick (15 mg/cm^2) ^{45}Sc target. The beam energy fulfilled the Cline safe energy condition [8] which ensures a purely electromagnetic excitation.

The γ rays depopulating Coulomb-excited states were detected in the EAGLE array [9], which was comprised of 16 Compton suppressed high-purity germanium (HPGe) detectors. The total photo-peak efficiency was 0.9% at 1112 keV. It was a thick target measurement, without particle-gamma coincidences. The collected γ-ray energy spectrum summed over 16 HPGe detectors is shown in Fig. 1. Several lines from the Coulomb-excited ^{45}Sc nuclei are marked, as well as the most intense γ-ray lines originating from the products of the reaction on target oxidation. In the ^{32}S + ^{16}O fusion–evaporation reaction, the ^{46}Ti, ^{46}V, ^{43}Sc isotopes were produced. The estimated cross section for the production of ^{45}Sc in this reaction is below 1 mb. Nonetheless, the measured intensities of the ^{45}Sc γ-ray lines

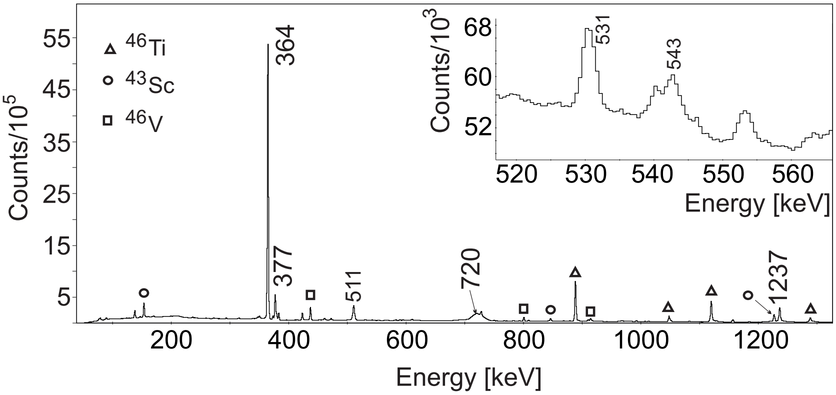

Fig. 1. Total γ-ray energy spectrum following Coulomb excitation of ^{45}Sc by a 70 MeV ^{32}S beam. The most intense γ-ray lines originating from the products of the reaction on target oxidation are marked with symbols.

were compared to the population of the ^{46}Ti states (being the most intense fusion–evaporation reaction product) and by taking into account the calculated cross sections, an upper limit for the number of counts not resulting from the Coulomb excitation of ^{45}Sc was obtained. In the performed measurement, up to 5% of the registered γ-ray intensities in ^{45}Sc may origin from the fusion–evaporation reaction. This experimental uncertainty has been included in the analysis of the collected data.

The γ-ray energy spectrum shows that the negative-parity ground-state structure has been populated, and γ rays decaying from low-lying states in the positive-parity isomeric band (excited via E3 transitions) can be seen as well. The Coulomb-excited states in ^{45}Sc populated in the present measurement are shown in Fig. 2. The observation of the 531 and 543 keV lines confirmed that the positive parity band built on the low-lying 12.4 keV isomeric state was populated in the present projectile–target combination via the Coulomb-excitation process. Moreover, the observed branching ratio for those lines confirms the identification.

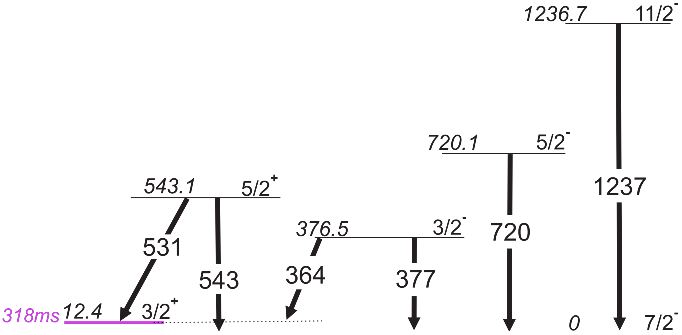

Fig. 2. The level scheme of ^{45}Sc depicting γ-ray transitions observed in the present experiment. Energies are given in keV.

3. Data analysis and results

The Coulomb excitation least-squares fitting code GOSIA [10] was used for data analysis. The programme fitted a set of reduced matrix elements to the measured γ-ray intensities and to other known spectroscopic data such as level lifetimes, branching ratios and E2/M1 mixing ratios. Those additional spectroscopic data (taken from NNDC nuclear data base [11] and listed in Tables I and II, were used as supplementary data points in the fit. The exact reproduction of the experimentally observed γ-ray intensities required integration over a very wide scattering angle range (from 10° to 180°) and over the range of bombarding energies resulting from the projectile energy loss in a target.

TABLE I

Half-lives of the excited states populated in the Coulomb excitation experiment, taken into account in the current analysis.

State	$11/2^-$	$5/2^-$	$3/2^+$	$5/2^+$
$T_{1/2}$ [ps]	1.80 ± 0.10	0.206 ± 0.016	$(318 \pm 7) \times 10^6$	5.5 ± 0.6

TABLE II

Branching ratios and mixing ratios δ(E2/M1) taken into account in the current analysis.

Energy [keV]	Branching ratio	Transition	δ(E2/M1)
377/364	0.0911 ± 0.0020	$5/2^- \to 7/2^-$	0.14 ± 0.05
543/531	0.705 ± 0.009	$5/2^+ \to 3/2^+$	-0.55 ± 0.11

Since E2 and E3 transition moments dominate the Coulomb excitation process [12, 13], they can be determined from intensities of γ rays depopulating the states of interest. The positive-parity, low-lying states belonging to the intruder band in ^{45}Sc (in Fig. 2), were excited via E3 transitions.

The impact of the reduced transition probability $B(\mathrm{E3};7/2^- \to 5/2^+)$ on the excitation process was analyzed in function of the $B(\mathrm{E3};7/2^- \to 3/2^+)$. The $B(\mathrm{E3};7/2^- \to 5/2^+)$ value was fitted to the experimental data with the B(E3) from the ground state to the isomeric state fixed. The differences in obtained χ^2 values were negligible. The result of this analysis, presented in Fig. 3, leads to the conclusion that the $B(\mathrm{E3};7/2^- \to 5/2^+)$ value has to be lower than 1.7 W.u.

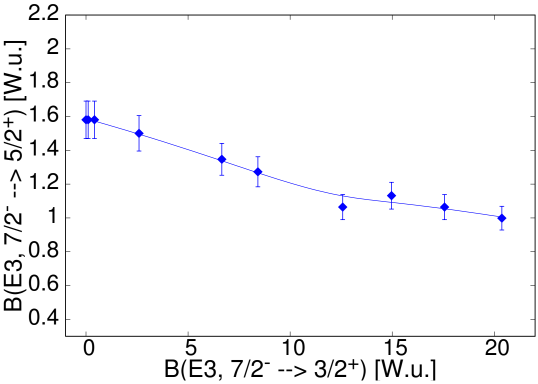

Fig. 3. Dependence of $B(\mathrm{E3};7/2^- \to 5/2^+)$ fitted to the experimental data on the assumed value of $B(\mathrm{E3};7/2^- \to 3/2^+)$. The solid line shows the trend.

To disentangle contributions from the $B(\mathrm{E3};7/2^- \to 3/2^+)$ and $B(\mathrm{E3};7/2^- \to 5/2^+)$ transition probabilities, a complementary measurement was performed at the Inter University Accelerator Center in New Delhi. The ongoing analysis will allow to determine with better accuracy the excitation probabilities from the ground state to the isomeric band in ^{45}Sc.

This work was supported by the National Science Centre, Poland (NCN) under the FUGA 3 postdoctoral fellowship grant No. DEC-2014/12/S/ST2/00483 and under the HARMONIA grants: No. DEC-2013/08/M/ST2/00591, No. DEC-2013/08/M/ST2/00257 and No. DEC-2013/10/M/ST2/00427. It received funding from the European Union's Horizon 2020 ENSAR2 Research and Innovation Programme under grant agreement No. 654002. The authors would like to thank the European Gamma-Ray Spectroscopy Pool GAMMAPOOL for the loan of the detectors for EAGLE. One of the authors (M.S.) acknowledges the support from the National Science Centre, Poland (NCN) under the fellowship grant POLONEZ-1(2015/19/P/ST2/03008), funded from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie Grant Agreement No. 665778.

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