SHELLS AND SHAPES IN THE ^{44}S NUCLEUS*

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(Received February 21, 2011)

The results obtained from electron and in-beam spectroscopy experiments reveal that the ^{44}S nucleus is located in a transitional region between the spherical ^{48}Ca and the oblate ^{42}Si. The comparison of the results with Large Scale Shell Model calculations points towards prolate-spherical shape coexistence where the ground state becomes the intruder configuration due to quadrupole excitations across the $Z = 14$ and $N = 28$ shell gaps.

DOI:10.5506/APhysPolB.42.533
PACS numbers: 23.20.Lv, 25.70.Mn, 27.40.+z, 29.30.Kv

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", August 30–September 5, 2010, Zakopane, Poland.

1. Introduction

It is already several years since our understanding of nuclear structure has changed. We no longer believe in the existence of universal magic numbers. On the contrary, thanks to new experimental data, it has been proven that, when approaching the drip line, nuclei with magic numbers of neutrons might lose their spherical character and become deformed. A clear example of such phenomena is the ^{42}Si nucleus with $N = 28$. The observation of a low lying 2_1^+ state was interpreted to be originated from quadrupole excitations across the $Z = 14$ and $N = 28$ shell gaps; thus ^{42}Si has an oblate deformation [1]. This interpretation has been confirmed recently by the $B(E2 : 2^+ \rightarrow 0^+)$ measurement [2]. In order to understand how deformation develops from the spherical ^{48}Ca to the deformed ^{42}Si, it is interesting to study the transitional nucleus ^{44}S. ^{44}S has been previously studied in Ref. [3, 4, 5]. All the experimental outcomes point to the shape-coexistence character of this nucleus, although different interpretations concerning the specific deformation were given. The new data provide a consistent picture of this nucleus and reveal a most likely prolate-spherical shape coexistence in ^{44}S.

2. Experimental details

The ^{44}S nucleus has been studied in two independent experiments at the Grand Accélérateur d'Ions Lourds (GANIL) facility. The first one focused on electron spectroscopy and delayed γ-emission. ^{44}S was produced by fragmentation of a ^{48}Ca primary beam at $60A$ MeV ($I \sim 2\ e\mu A$) in a ^{9}Be target of 138 mg/cm^2 thickness. The ions of interest were separated in the LISE spectrometer by means of the $B\rho$–ΔE–$B\rho$ method. Isotope identification was performed by a combined measurement of the energy loss, magnetic rigidity and Time-of-Flight (TOF) in an event-by-event basis. After separation, the ions came to rest in a kapton foil at the last focal point of the spectrometer. Above and below the foil, a stack of four 4 mm thick Si(Li) detectors was placed in order to record the delayed electrons within a time window of 20 μs after implantation. Moreover, the delayed γ-rays were measured in two high purity Ge clover detectors of the EXOGAM array located at the side of the implantation foil. The second experiment was dedicated to in-beam spectroscopy. In this case, ^{44}S was produced in a two-step reaction. A secondary beam of ^{45}Cl was produced in the fragmentation of ^{48}Ca at $60A$ MeV onto a 200 mg/cm^2 C target and separated in the ALPHA spectrometer at GANIL. The TOF measurement and ΔE information necessary for the identification of the cocktail beam were provided by micro-channel plate and Si detector, respectively. The selected ^{45}Cl nuclei undergo fragmentation in a 195 mg/cm^2 ^{9}Be target to produce the

^{44}S. The reaction residues were separated in the SPEG spectrometer and the identification was performed using the standard detectors composed of drift chambers and plastic scintillator. The prompt-γ radiation was recorded by a stack of 74 BaF_2 detectors of the Château de Cristal array placed in close geometry surrounding the secondary target.

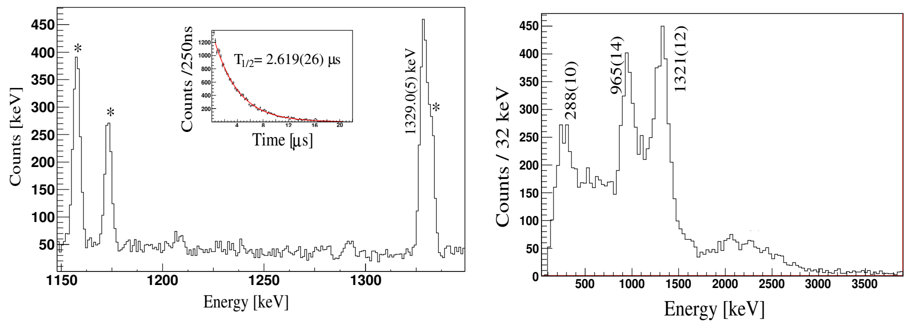

Fig. 1. Left: Delay gamma spectrum following the ^{44}S implantation. Background lines are shown with *. The inset shows the time distribution of the 1362.5 keV electrons emitted in the 0_2^+ isomeric state decay to the ground state. Right: Prompt radiation associated to the decay of ^{44}S. Previously reported transitions are observed and in addition high energy γ rays above ~1700 keV were measured.

3. Results and discussion

The 0_2^+ isomeric state in ^{44}S at 1365 keV excitation energy decays by internal conversion and internal pair formation to the ground state (g.s.). In the first experiment, the delayed electron spectrum following implantation was measured. The half-life ($T_{1/2}$) of the isomeric state was extracted to be 2.619(26) μs by fitting the time distribution of electrons with a single exponential decay curve and it is in agreement with the previously reported value in Ref. [5] (inset of Fig. 1, left). Additionally, a weak branch to the 2_1^+ state (1329 keV excitation energy) was observed by the following $2_1^+ \to 0_1^+$ γ transition (Fig. 1, left) allowing a calculation of the decay branching ratio (BR $= \lambda(E2)/\lambda(E0)$) of the 0_2^+ state, yielding 0.163(13). Moreover, the monopole strength and the $B(E2 : 2_1^+ \to 0_2^+)$ value were determined by the combined measurement of BR and $T_{1/2}$ to be 8.7(7) $\times 10^{-3}$ and 8.4(26) e^2 fm^4, respectively. The large difference between the previously measured $B(E2 : 0_1^+ \to 2_1^+)$ value [3] and the $B(E2 : 0_2^+ \to 2_1^+)$ value obtained in this experiment indicates a low mixing between the two 0^+ states and consequently points out the shape-coexistence character of ^{44}S. This interpretation is supported by the low measured ρ_0, which is the smallest in this mass region. Further information concerning the experimental outcome can be found in Ref. [6]. In the second experiment, the prompt γ radiation associated to the decay of ^{44}S was measured. The singles γ-ray spectrum is shown in Fig. 1, right. The previously reported transitions at 1321, 965 and 288 keV are observed although the 2632 keV γ-ray [4] could not be confirmed from this work. A $\gamma\gamma$-coincidence analysis was performed for the first time in this nucleus. The spectrum gated on the 1321 keV γ line reveal the existence of two well differentiated peaks at high energy indicating that the γ distribution observed in the singles spectrum between 1700 and 2300 keV is formed by three peaks where a γ-ray of about $\sim$ 2100 keV is not in coincidence with the $2^+_1 \rightarrow 0^+_1$ transition. The latter γ-ray is tentatively assigned to be the $(2^+_2) \rightarrow 0^+_1$ transition. Indeed, the (2^+_2) state mainly decays to the g.s. of ^{44}S due to the energy dependence of the reduced transition probabilities. More details of the experimental outcome will be available in a forthcoming publication [7].

The experimental data were compared to the results of Large Scale Shell Model (LSSM) calculations using the SDPF-U interaction [8] and the full $sd(fp)$ valence space for protons (neutrons). Good agreement for the excitation energy of the states and the reduced transition probabilities is found between theory and experiment. Moreover, the shell model predicts the existence of a prolate band built on top of the g.s. which is connected by large $B(E2)$ values and same quadrupole moments (Q). In addition, the LSSM calculations predict a 2^+_2 state at 2140 keV with $Q = -0.3\ e\,\mathrm{fm}^2$ on top of the 0^+_2 level which corresponds well with the experimentally tentatively assigned (2^+_2) state at $\sim$ 2100 keV. Considering the calculated reduced transition probabilities from the shell model and the experimental excitation energies, the 2^+_2 state mainly decays to the g.s. with 83% branching ratio. Therefore, it is concluded that ^{44}S has a prolate-spherical shape coexistence with the intruder configuration being the g.s. with deformation $\beta \simeq 0.25$ and rather spherical structures of the 0^+_2 and 2^+_2 levels. The onset of collectivity in ^{44}S is caused by the combined action of proton–neutron tensor forces leading to a compression of the energy difference between single particle states; thus quadrupole excitations develop across the $Z = 14$ and $N = 28$ shell gaps.

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