\(\gamma\)-ray spectroscopy of excited states in \(^{61}_{30}\text{Zn}_{31}\)

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Abstract. The \(^{61}_{30}\text{Zn}_{31}\) isotope has been produced at the Oak Ridge National Laboratory in the fusion-evaporation reaction \(^{40}\text{Ca}(^{24}\text{Mg}, 2p\nu)^{61}\text{Zn}\) at 104 MeV. The experimental set-up allowed \(\gamma\)-rays to be detected in the CLARION Ge detector array in coincidence with the detection of recoiling nuclei in the focal plane at the end of the recoil mass spectrometer. This provides a unique identification of \(\gamma\)-rays belonging to \(^{61}\text{Zn}\). The excited states have been explored by means of recoil-\(\gamma\gamma\) coincidences, and the resulting decay scheme comprises almost 70 transitions. The data reveal numerous non-yrast states and suggest a revised spin and parity assignment for a previously observed superdeformed band. The resulting decay scheme is compared to predictions from different sets of large-scale shell model calculations.

PACS. 21.60.Cs Shell model – 23.20.En Angular distribution and correlation measurements – 23.20.Lv \(\gamma\) transitions and level energies – 27.40.+z \(39 \leq A \leq 58\)

1 Introduction

The \(^{61}_{30}\text{Zn}_{31}\) nucleus lies just beyond the \(N = Z = 28\) shell closure, with two protons and three neutrons occupying the subshells up to the next closure at \(N = Z = 50\). The subshells placed in between the two shell closures are the negative-parity \(2p_{3/2}, 1f_{5/2}\) and \(2p_{1/2}\) orbitals in the upper \(fp\) shell, and the positive-parity \(\ell = 4\) \(1g_{9/2}\) intruder orbital. Because of its high-j nature, excitations into the latter influence or even dominate the level sequences of \(N \sim Z, A \approx 60\) nuclei already at moderate excitation energies. Examples of this are \(^{59,61}\text{Cu}\) and \(^{61}\text{Zn}\) [1–3]. An additivity principle was derived in ref. [1], which relates the amount of quadrupole deformation to the number of particles in the \(1g_{9/2}\) orbital and holes in the \(1f_{7/2}\) orbital, providing a natural transition from spherical structures to superdeformed (SD) rotational sequences.

Theoretically, the inclusion of the \(1g_{9/2}\) orbital in state-of-the-art shell-model calculations is difficult due to the center-of-mass problem, here caused by insufficient separation of center-of-mass and relative coordinates of the 61 nucleons (cf. p. 447 and p. 482ff in ref. [4]).

Another facet of \(N \sim Z, A \approx 60\) is the investigation of isospin symmetry by studying mirror nuclei, i.e. nuclei with the same mass number but with interchanged proton and neutron numbers. The mirror nucleus of \(^{61}_{30}\text{Zn}_{31}\) is \(^{61}_{31}\text{Ga}_{30}\), where the first few excited states recently have been established [5]. To obtain solid information on isospin-breaking effects from mirror nuclei, detailed spectroscopic knowledge of the less exotic partner—in this case \(^{61}\text{Zn}\)—is necessary.

In the present paper we report on the investigation of excited states in \(^{61}\text{Zn}\). Previous data aimed to extend an existing [6,7] low-spin level scheme [2], to determine parity-changing \(E1\) transitions [3], and to search for superdeformed rotational bands [8]. The most recent decay scheme of normally deformed structures in \(^{61}\text{Zn}\) comprises some 25 \(\gamma\)-ray transitions reaching over 9 MeV excitation energy and a few spin and parity assignments [2], which were refined in ref. [3]. Our analysis provides a firm decay scheme with a considerable increase to almost 70 transitions ranging up to a spin \(I^\pi = 31/2^-\) state at an excitation energy of \(E_x = 10155\) keV. Interestingly, revised spin assignments of the low-lying levels based on ref. [3] and the current analysis affect the presumed, tentative spin assignments of the \(^{61}\text{Zn}\) SD band [8].
The experimentally observed energy levels in the \( ^{61}\text{Zn} \) nucleus are compared with shell model calculations using two different configuration spaces: i) the full \( fp \) space, neglecting excitations up to the \( 1\text{g}_9/2 \) orbital, and ii) a closed \( ^{56}\text{Ni} \) core with the five valence nucleons moving in and between the \( 1\text{f}_{5/2}, 2\text{p}_{3/2}, 2\text{p}_{1/2}, \) and \( 1\text{g}_9/2 \) orbitals.

This paper reports on the experimental details including the set-up (sect. 2), the data analysis (sect. 3) and results (sect. 4). Section 5 deals with the shell model calculations involving both of the above-mentioned configuration spaces.

2 The experiment

The experiment was conducted at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. In fusion-evaporation reactions of a 104 MeV \( ^{40}\text{Ca} \) beam, impinging on a 99.92\% isotropically enriched \( ^{24}\text{Mg} \) target foil of thickness 0.3 mg/cm\(^2\), \( ^{64}\text{Ge} \) compound nuclei are formed. The \( ^{61}\text{Zn}_{31} \) nuclei are then produced via the evaporation of two protons and one neutron.

The experimental set-up comprised the germanium detector array, CLARION [9], consisting of ten Ge clover detectors placed in a three ring configuration (90°, 132°, and 154°), and the Recoil Mass Spectrometer (RMS) using the split anode Ionisation Chamber (IC) at the focal plane [10]. The distance between the clover detectors and the target was 20.0 cm. In that configuration CLARION has an overall \( \gamma \)-ray detection efficiency of about 2.3\% at 1.3 MeV \( \gamma \)-ray energy. At the end of the experiment CLARION was energy calibrated using the three standard \( \gamma \)-ray sources \( ^{152}\text{Eu}, ^{133}\text{Ba}, \) and \( ^{88}\text{Y} \).

The RMS separates the recoils in mass-to-charge ratio, \( A/Q \), where \( Q \) denotes the charge state of the recoiling nuclei. For a given charge state masses are thus determined by their horizontal position at the focal plane of the spectrometer. These positions are measured by a position-sensitive grid, placed inside the IC. Information about the energy and the atomic number, \( Z \), of the recoils is provided via the differential energy loss information from the split anode in the IC. This information is comprised in the \( R_{13} \) parameter, which relates the energy loss in the first and the third part of the IC anode via the ratio between the two. The \( R_{13} \) parameter is introduced and explained further in ref. [5].

3 Analysis

In total there are three isotopes of mass \( A = 61 \) observed in the present fusion-evaporation reaction: \( ^{61}\text{Cu}_{32}, ^{61}\text{Zn}_{31} \),