Gamma-ray spectroscopy of the doubly magic nucleus $^{56}$Ni

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Abstract. The doubly magic $N = Z$ nucleus $^{56}$Ni has been investigated with two fusion-evaporation reactions; $^{40}$Ca$(^{28}$Si, 3o)$^{54}$Ni at a beam energy of 122 MeV and $^{58}$Si$(^{28}$Si, 2p2n)$^{56}$Ni at 130 MeV. To detect $\gamma$-rays in coincidence with evaporated particles the $\gamma$-detector array Gammasphere was used in conjunction with the charged-particle detector system, Microball and a 1π neutron detector array. Results include a significantly extended level scheme of $^{56}$Ni, which is compared to large-scale shell model calculations in the fp shell. The experimental and theoretical results agree to a large extent, with one notable exception; the theoretical model fails to predict the proper sequence of the yrast and yrare \(8^+ \) states.

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

Fundamental building blocks within nuclear structure are the experimentally observed shell gaps associated with the magic numbers, which are very well reproduced by the nuclear shell model. In this model the $N = Z = 28$ nucleus $^{56}$Ni is the first doubly magic nucleus to be described by the inclusion of the spin-orbit force in the nuclear mean-field potential. The spin-orbit force causes a splitting within the fp shell: the energetically favoured $j = \ell + s$ orbit 1f$\ell/2$ separates from the 2p$\ell/2$ and 1f$\ell/2$ orbitals, also called the upper fp shell, thus, creating the shell gap at particle number 28. Consequently, the expected leading ground-state configuration of $^{56}$Ni has all orbitals filled up to and including the 1f$7/2$ orbit. However, the probability for this ground-state configuration was found to range from some 50–70% in contemporary shell model approaches, depending on the interaction used [1]. These values are substantially lower than the corresponding numbers for the nearby doubly magic nucleus $^{48}$Ca (94%), which has been taken as a sign of $^{56}$Ni representing a rather soft doubly magic core [1].

Other signatures of a double shell closure include a high excitation energy of the first $2^+$ state and a low quadrupole excitation strength to that state. The energy of the first $2^+$ state in $^{56}$Ni is established at 2.7 MeV. Though this energy is reasonable for single-particle excitations, it is relatively low compared to other doubly magic nuclei. For example, the first $2^+$ state in $^{48}$Ca is located at 3.8 MeV. The reduced transition strength has been measured to be $B(E2; 0^- \rightarrow 2^+) \approx 560 \epsilon^2$ fm$^4$ via proton scattering [2] and intermediate-energy Coulomb excitation [3, 4]. Contemporary shell model calculations [1] predict $B(E2; 0^- \rightarrow 2^+) \approx 550 \epsilon^2$ fm$^4$, i.e., perfect agreement between theory and experiment. With respect to the much lower value of $B(E2; 0^- \rightarrow 2^+) \approx 84 \epsilon^2$ fm$^4$ in $^{48}$Ca this is yet another hint for the softness of the $^{56}$Ni core.

The question to be addressed in this study is whether or not this degree of consensus remains for the complete set of experimentally known states in $^{56}$Ni. Early experimental work on $^{56}$Ni includes an in-beam $\gamma$-ray spectroscopic study [5], establishing the yrast sequence up to...
a tentative spin and parity of $I^\pi = 10^+$. A subsequent high-spin study of $^{56}$Ni led to the discovery of two superdeformed rotational structures [6], While one band can readily be explained by Hartree-Fock-based mean-field models and $fp$ shell model calculations, the second band requires the excitation of one particle into the $1g_{9/2}$ intruder orbital [6-8].

In this paper results from two data sets are combined. This more than doubles the number of known $\gamma$-ray transitions and excited states in $^{56}$Ni. The experimental data are compared with the results of a large scale, state-of-the-art shell model calculation. In particular, electromagnetic decay properties are investigated in detail, revealing deficiencies in the theory to properly describe all yrast states in $^{56}$Ni.

2 Experiment and data analysis

Excited states in $^{56}$Ni were studied with two different heavy-ion fusion-evaporation reactions initiated at the 88$^\text{th}$ cyclotron at Lawrence Berkeley National Laboratory and at the ATLAS facility at Argonne National Laboratory. Experiment 1 utilized a 28$^\text{th}$Si beam with an energy of 122 MeV impinging on a 0.5 mg/cm$^2$ thin 40Ca target, creating a compound nucleus of $^{50}$Se. Through emission of 3$^\text{a}$ particles, $^{56}$Ni is obtained. The 99.98% enriched target foil was sandwiched between two thin layers of gold to prevent oxidation. The $\gamma$-rays were detected in the Gammasphere array [9], which comprised 101 Compton-suppressed Ge-detectors with the Heavimet collimators removed. This allows for $\gamma$-ray multiplicity and sum-energy measurements. Evaporated light charged particles were detected with the 4$\pi$ CsI-array Microball [10]. Events were collected if four or more Compton-suppressed $\gamma$-rays were detected. For further information on the experiment see ref. [11].

In experiment 2, a beam of 32$^\text{S}$ collided with a 28$^\text{th}$Si target foil at a beam energy of 130 MeV. This reaction produced the compound nucleus $^{50}$Zn, which generates $^{56}$Ni by emission of two protons and two neutrons. The 0.5 mg/cm$^2$ thin 28$^\text{th}$Si target was enriched to 99.90% and supported either with 1.0 mg/cm$^2$ Au or 1.0 mg/cm$^2$ Ta facing the 130 MeV 32$^\text{S}$ beam. The energy loss in the foil amounts to 5 MeV, thus the effective beam energy was 125 MeV. Here the Gammasphere comprised 78 Ge-detectors with the Heavimet collimators removed as well. Microball was used to measure and identify light charged particles. The five most forward rings of Gammasphere were replaced by the Neutron Shell [12], consisting of 30 liquid scintillator detectors to enable neutron detection. The trigger used was either four or more $\gamma$-rays in coincidence, or three or more $\gamma$-rays in coincidence with one or more pre-discriminated neutrons. More details can be found in ref. [13].

In the analysis of both experiments, discrimination between protons and $\alpha$ particles is crucial in creating clean particle gated spectra with sufficient statistics. Therefore, each Microball event was associated with time, energy, and charge-ratio signals [10] obtained through pulse shape techniques. These signals were plotted in three two-dimensional spectra, and particles were identified only after fulfilling gate conditions in all three maps. Subsequently, the $\gamma$-ray energy resolution was optimized by an event-by-event kinematic reconstruction method to reduce the effect of the Doppler broadening due to the evaporated particles.

To distinguish between neutron- and $\gamma$-ray signals from the neutron detectors, pulse shape discrimination techniques were utilized. Four signals from each neutron detector were digitized: time of flight (TOF), zero-cross-over time (ZCO), energy, and the tail of the energy signal [12]. Two-dimensional gates on several combinations of these signals provided a clean distinction between neutrons and $\gamma$-rays [9,12].

In both experiments, the events were sorted off-line into $E_{\gamma}-E_{\gamma}$ correlation matrices. These were subject to appropriate evaporated particle conditions, i.e., the $\gamma$-rays had to be in coincidence with three $\alpha$ particles (3$\alpha$) for experiment 1, and with two protons and two neutrons (2p2n) for experiment 2.

The main contaminating reaction channels in the $\gamma$-ray spectra are those for which one proton escaped detection, namely, the 3p2n and 3$\alpha$1p channels, respectively, leading to the well-known isotope $^{58}$Co in both cases. Some contaminations from the 2p1n and 3p1n channels ($^{57}$Ni and $^{56}$Co) were also present in the 2p2n selected $\gamma$-ray spectra from experiment 2. This is due to the remaining one-neutron scattering events, which can mimic two-neutron events, but unfortunately passed the two-neutron selection criteria [13]. In experiment 1, possible misidentification of two protons as one $\alpha$ particle results in the inclusion of $^{58}$Ni created in the 2$\alpha$2p evaporation channel, as can be seen in fig. 3. Nevertheless, all these contaminations can easily be handled or eliminated by studying $\gamma$-ray matrices and spectra in coincidence with the respective number and type of evaporated light particles. The analysis employed the Radware software package [14] and the Cologne spectrum analysis code Tv [15].

The spins and parities of the states were determined by utilizing yields measured by Ge detectors placed at different angles with respect to the beam axis. In experiment 1, 15 detectors at forward and 15 detectors at backward angles were combined to create a “pseudo” ring at an effective angle of 30°. Similarly, 28 detectors between 80° and 100° make up a “pseudo” ring placed at an average angle of 83°. This is based on the fact that the angular distribution of $\gamma$-rays is symmetric with respect to the reaction plane. Particle-gated $\gamma\gamma$ matrices with $\gamma$-rays detected at 30° (alternatively 83°) vs. $\gamma$-rays detected anywhere in the array were generated. From these matrices the intensity ratios

$$R_{30-83} = \frac{I_\gamma(30°)}{I_\gamma(83°)}$$

(1)

can be obtained [16]. These allow the deduction of spin and parity for the excited states, as $\gamma$-rays of different multipolarities have different angular distributions and, hence $R_{30-83}$ values. Stretched quadrupole transitions are predicted to have $R_{30-83} \sim 1.3$, whereas an $R_{30-83} \sim 0.8$