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Test of the $\pi g_{7/2}$ subshell closure at $Z = 58$

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ABSTRACT

A simultaneous lifetime and relative g-factor measurement of the 2_1^+ levels in ^{138,142}Ce was performed using the Time Dependent Recoil Into Vacuum (TDRIV) technique. The excitation mechanism was Coulomb excitation in inverse kinematics, and the experimental setup included the Yale plunger device and the Gammasphere array. The latter was used to extract angular distributions for the $2_1^+ \to 0^+$ γ-ray transitions at various target-to-stopper distances. A $g(2_1^+)$ factor of 0.26(8) for ^{138}Ce was obtained relative to the literature value of $g(2_1^+) = 0.21(5)$ in ^{142}Ce. In addition, high-precision values of the $B(\mathrm{E2}; 2_1^+ \to 0^+)$ strengths were obtained. The new data support a proposed subshell closure for the $\pi g_{7/2}$ orbital at $Z = 58$.

1. Introduction

Studying collective excitations in nuclei gives insight into the mechanisms responsible for driving these strongly interacting many-body systems toward deformation. Highly correlated collective structures originate from a coherence in the independent motion of the neutrons and protons in a mean field modified by the residual interactions between the nucleons. Investigations of isoscalar and isovector excitations in a chain of isotopes provide extensive complementary information on the proton–neutron interaction. Often, the underlying single-particle structure has been found to influence the stability of such collective excitations, showing an interesting interplay between collective and the single-particle degrees of freedom [1,2]. This competition results in an evolution of nuclear properties with N and Z, as well as with excitation energy and angular momentum.

In recent studies along the $N = 80$ ^{134}Xe [3], ^{136}Ba [4] and ^{138}Ce [5] isotones, a large impact of the single-particle structure on collective mixed-symmetry states (MSSs) was observed. In the framework of the interacting boson model-2 [6,7], MSSs are described as excitations in which protons and neutrons move partially out of phase. Their fully-symmetric analog states (FSSs), i.e., 2_1^+ states in even–even nuclei, where the two types of nucleons move in phase, have similar configurations and are lower in excitation energy. A characteristic property of MSSs is their connection to FSSs with the same number of quadrupole bosons via strong M1 transitions.

In ^{138}Ce, the M1 transition strength between the higher-lying $(2_{1,ms}^+)$ mixed-symmetry level and the first excited 2^+ state was found to be fragmented [5]. In contrast, in ^{134}Xe [3] and ^{136}Ba [4] the M1 strength remains largely concentrated in a single transition. Moreover, the total measured M1 strength is smaller for ^{138}Ce than for the other isotones. These observations were attributed to a lack of shell stabilization in ^{138}Ce [5], based on calculations within the quasiparticle–phonon-model (QPM) [8,9]. In this concept, the purity of the $2_{1,ms}^+$ state gets “washed out” in ^{138}Ce due to its single-particle structure. In a simplified independent-particle model, the complete filling of the $\pi g_{7/2}$ orbital at $Z = 58$ leads to configurations involving the higher-lying $\pi d_{5/2}$ orbital for the FS and MS one-phonon 2^+ states. Multi-phonon 2^+ states have

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similar proton configurations. Hence, mixing of the one-phonon MSS with nearby, higher-seniority 2^+ states can occur in ^{138}Ce, in contrast to ^{134}Xe and ^{136}Ba, where the $\pi g_{7/2}$ orbital is not fully occupied and the $2^+_{1,ms}$ state remains rather pure. Extending the shell stabilization concept to ^{140}Nd, one would expect a similar fragmentation of M1 strength as in ^{138}Ce. However, although both $2^+_{3,4} \to 2^+_1$ decays have dominant M1 character [10], only the absolute $B(\mathrm{M1}; 2^+_4 \to 2^+_1)$ strength has been measured [11], and no final conclusion can be drawn at this point.

Large-scale Shell Model (LSSM) calculations were also carried out [12] to study the evolution of MSSs in the $N = 80$ isotones. The wave functions of low-lying states in all $N = 80$ isotones up to $Z = 60$ revealed significant mixing of the $\pi g_{7/2}$ and $d_{5/2}$ configurations and no pronounced shell closure was found [12]. Additional pairing strength was needed to achieve agreement in total M1 rates. However, the fragmentation of the M1 strengths was not reproduced quantitatively. Contrary to the QPM, the LSSM predicts an isolated MSS in ^{140}Nd.

Due to the conflicting conclusions on a $\pi g_{7/2}$ subshell closure within the two models, the main components of the states in question need to be verified experimentally. The magnetic moment of a state is a sensitive probe of its wave function. Therefore, a measurement of the g factor of the 2^+_1 level in $Z = 58$, ^{138}Ce was performed for the first time using Gammasphere and the Time Dependent Recoil Into Vacuum technique (TDRIV). The 2^+_1 level in this nucleus is the fully-symmetric analog of the $2^+_{1,ms}$ state [12]. Constraining the proton–neutron contributions in the wave function of the 2^+_1 state serves as a direct test for whether enhanced pairing strength is needed in the region, which impacts the structure and purity of MSSs. In addition, the simultaneous high-precision re-measurement of $B(\mathrm{E2})\downarrow = B(\mathrm{E2}; 2^+_1 \to 0^+)$ strengths gives further insight into the existence of a possible subshell at $Z = 58$.

2. Experimental technique

Low-lying excited states in ^{138,142}Ce were populated via Coulomb excitation in inverse kinematics. ^{142}Ce and ^{138}Ce beams of intensity ∼1.7 enA and energies of 494 MeV and 480 MeV, respectively, were provided by the ATLAS accelerator at Argonne National Laboratory. The experimental setup consisted of the Yale plunger device [13] positioned at the center of the Gammasphere array [14] comprising 100 HPGe detectors arranged in 16 rings. The plunger hosted a 0.85-mg/cm^2-thick ^{24}Mg target for Coulomb excitation, followed by a ^{nat}Cu stopper of 15.7 mg/cm^2 thickness that stops the beam but allows the target recoils to pass through. The target-to-stopper distance, d_m, (relative to the point of electrical contact) was varied between ∼1 μm and 3 mm to enable a lifetime analysis of the states populated in the reaction with the Recoil Distance Doppler Shift (RDDS) method [15], as well as to measure the deorientation of the nuclear spin in vacuum. The Mg recoils were detected by a 300-mm-thick silicon detector kept at 0° with respect to the beam axis, at a distance of ∼8 mm behind the target. This detector covered a laboratory solid angle of ±29.7°. Angular distributions of deexciting γ rays were extracted at all target-to-stopper distances. A particle–γ coincidence, or a downscaled particle-singles or γ-singles event trigger, was required.

Transitions from excited states in ^{138,142}Ce are displayed in Fig. 1. The average velocities, v, of ^{138,142}Ce recoils, calculated from the observed Doppler shifts of the $2^+_1 \to 0^+$ transitions, are 5.6% and 5.8% of the velocity of light, respectively. Due to such large velocities, the Doppler-shifted components of γ transitions (SH) are well separated from the ones emitted from the nuclei at rest (US) for the detector rings with azimuthal angles less than 58° and greater than 122° with respect to the beam axis (see insets in Fig. 1). For angles near 90°, Monte Carlo simulations were used to estimate the centroids and shapes of SH and US components. The Monte Carlo code [16,17] simulates the time behavior of the velocity of the ions of interest in three dimensions. It takes into account the reaction kinematics, the slowing down in the target and stopper, and the free flight in vacuum. Details about the determination of stopping powers can be found in Ref. [18]. A γ-ray spectrum for the 79.2° detector ring is compared in Fig. 2 to the Monte Carlo simulations fitting the relative heights of the various peak components. A more detailed description of a similar analysis, including the fit of the stopping component at forward and backward angles is provided in Refs. [19,20].

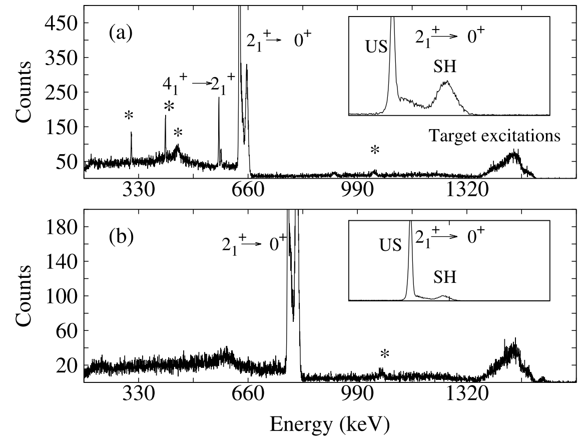

Fig. 1. Gamma-ray spectra of ^{142}Ce (a) and ^{138}Ce (b) for the target-to-stopper distances of 2 μm, 5 μm, 10 μm and 15 μm added together and measured in a forward detector ring of Gammasphere. The visible $2^+_1 \to 0^+$ and $4^+_1 \to 2^+_1$ transitions are labeled. The $2^+_1 \to 0^+$ transition originating from the excitation of the Mg target is also visible. Gamma rays marked as (*) belong to small amounts of beam contaminants and background.

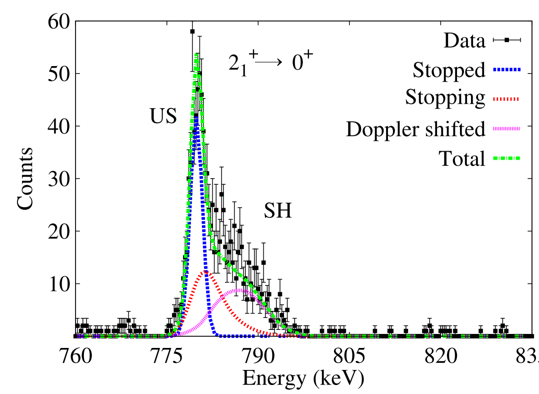

Fig. 2. Gamma-ray spectrum from ^{138}Ce for a detector ring at 79.2°. Monte Carlo simulations for different components are shown with dashed lines.

3. Results

The angular distributions of the $2^+_1 \to 0^+$ transitions are described by the standard formalism [21] for perturbed particle–γ correlations as

$$W(t,\theta_\gamma) = \sum_{k=0,2,4} Q_k B_k R_k G_k(t) P_k\big(\cos(\theta_\gamma)\big), \tag{1}$$

where the Q_k coefficients take into account the attenuation due to the finite solid angle of the Ge detectors [22], B_k are the m state distribution coefficients, R_k are the Racah coefficients [21],