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The impact of the intruder orbitals on the structure of neutron-rich Ag isotopes

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ABSTRACT

The low-lying high-spin yrast band structure of neutron-rich $^{113,118-121}$Ag has been established for the first time using prompt γ-ray spectroscopy of isotopically identified fission fragments produced in the ^{9}Be(^{238}U, $f\gamma$) fusion- and transfer-induced fission processes. The newly obtained level energies follow the systematics of the neighboring isotopes. The sequences of levels exhibit an energy inheritance from states in the corresponding Cd core. A striking constancy of a large signature splitting in odd-A Ag throughout the long chain of isotopes with $50 < N < 82$ and a signature inversion in even-A Ag isotopes, which are indications of triaxiality, were evidenced. These observed features were reproduced by large-scale shell-model calculations with a spherical basis for the first time in the Ag isotopic chain, revealing microscopically their complex nature with severely broken seniority ordering. The essential features of the observed signature splitting were further examined in the light of simplified, two-orbital shell-model calculations including only two intruder orbitals $\pi g_{9/2}$ and $\nu h_{11/2}$ from two consecutive shells above $Z = 50$ and $N = 82$ for protons and neutrons respectively, resulting in the $\pi g_{9/2}^{-3} \times \nu h_{11/2}^{m}$ configurations. The newly established bands were understood as fairly pure, built mainly on unique-parity intruder configurations and coupled to the basic states of the Cd core.

The collective and single-particle motion of the nucleons and their correlations can give rise to a variety of nuclear shapes, asymmetries, and excitation modes [1,2]. Triaxial nuclear shapes are directly manifested through the presence of various phenomena, like chirality and wobbling, and indirectly by signature splitting [1] and signature inversion. Gamma-ray spectroscopy is a major tool to experimentally explore the different facets of the above mentioned features [3]. Microscopic approaches of the shell model with a spherical basis (spherical shell model) are applied near shell closures while the deformed shell model (e.g. Nilsson model) with a deformed basis is used to describe mid-shell nuclei [4]. Large-scale shell-model calculations with a spherical basis can expand the calculable regions and can reproduce various aspects of nuclear structure from single-particle to collective motions [4] due to progress in computing power and associated techniques. However, there has been no attempt to account for the signatures of triaxiality in the framework of the spherical shell model in neutron-rich nuclei below Sn.

In neutron-rich nuclei below $Z = 50$, two intruder orbitals $\pi g_{9/2}$ and $\nu h_{11/2}$ lying near the Fermi surface are expected to play an important role. While going away from shell closures ($Z = 50$ and $N = 82$), the nucleon–nucleon correlations result in an increasing collectivity and associated deformations. In the case of axial deformation, the $\pi g_{9/2}$ orbital with a *high* angular momentum projection on the symmetry axis (Ω) and the $\nu h_{11/2}$ orbital with a *low* Ω, tend to drive the nucleus towards oblate and prolate deformation, respectively [5–7]. Hence, emergence of triaxial shapes is expected in this region, which can be associated with $\pi g_{9/2}^{n} \times \nu h_{11/2}^{m}$ configurations. Triaxial shapes have been shown to exist in neutron-rich isotopes near Ag (e.g. $^{112-118}$Rh [7,8] and $^{112-118}$Pd [9]) and the degree of triaxiality increases systematically in odd-Z isotopes, as one progresses from Y to Rh isotopes (Rh being in the vicinity of the $Z = 50$ shell closure) [2,10]. Esser et al. [11] established, using the systematics of the Pb region, that

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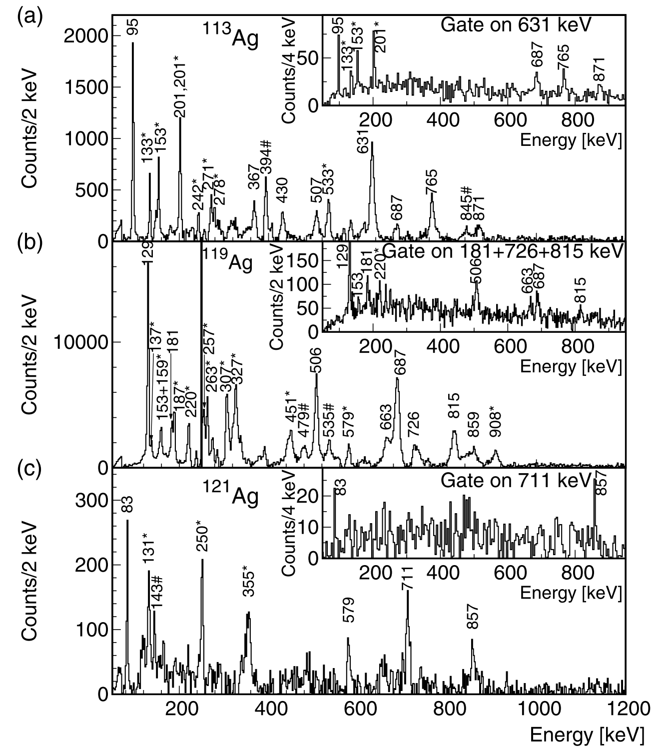

Fig. 1. The Doppler corrected γ-ray singles spectra for isotopically identified odd-A Ag isotopes (a) ^{113}Ag, (b) ^{119}Ag, and (c) ^{121}Ag. The ^{119}Ag singles spectrum is magnified by factor of 3 above 250 keV. γ–γ coincidence spectra are presented in the inset. Note that 201 keV in ^{113}Ag is a doublet (see text). The transitions assigned to side bands based on a coincidence between transitions are marked by (*). Transitions, not placed in the level scheme due to the lack of γ–γ coincidences, are marked by (#).

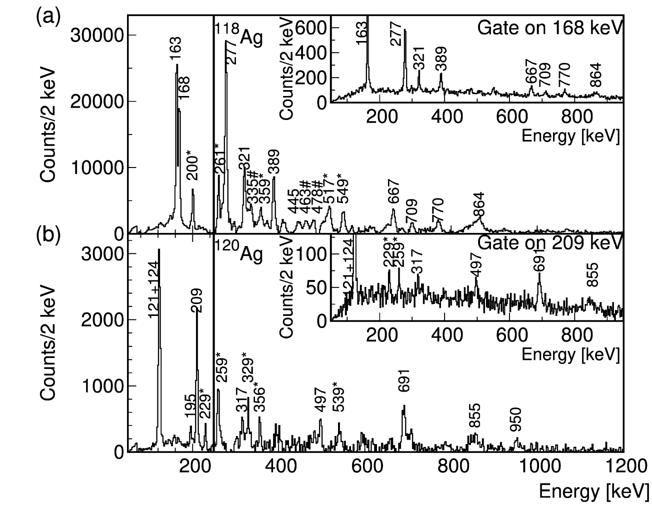

Fig. 2. The Doppler corrected γ-ray spectra for even-A Ag isotopes (a) ^{118}Ag and (b) ^{120}Ag. The singles spectra are magnified by 3 times above 250 keV. γ–γ coincidence spectra are shown in the inset. Note that the 121, 124 keV transitions are not resolved in (b) due to the 2 keV binning, but are resolved with a 1 keV/ch binning (see text). The labeling of the peaks is the same as in Fig. 1.

triaxiality reaches its maximum close to a shell closure and hence one could expect a large degree of triaxiality near Ag. Signatures of axial asymmetry have been established in the even-A Ag isotopes, i.e. γ-softness (^{106}Ag [12]), chirality (^{108}Ag [13]), and triaxial deformation (^{110}Ag [14]). In odd-A Ag isotopes chirality (^{107}Ag [15]) and triaxial deformation (^{109}Ag [14]) have been observed. For Ag isotopes with $A > 110$, the possibility of γ-softness in ^{115,117}Ag have been discussed [16]. Hence, the neutron-rich isotopes of Ag are an ideal region to explore nuclear structure properties related to triaxiality.

Theoretical interpretations for the region around the neutron-rich Ag isotopes were mainly carried out using deformed shell-model assuming a deformed core coupled to valence quasi-particles (e.g. triaxial rotor + particle model [7,17], tilted axis cranking model [18], triaxial projected shell-model [19], interacting boson model [20,21], and interacting boson–fermion plus broken pair model [22]). On the other hand, neutron-rich In and Cd isotopes were interpreted with the spherical shell model [23–26]. A microscopic view with the spherical shell model could bring a new perspective, e.g. the unexpected breaking of seniority (the number of unpaired nucleons) as observed in the neutron-rich In isotopes arising due to the proton–neutron interaction between the $\pi g_{9/2}$ and $\nu h_{11/2}$ orbitals [25]. The large dimensions associated with the relevant large-scale shell-model calculation limit its application in this region [26]. The $^{116–121}$Ag isotopes lie at the borderline of such large-scale shell-model calculations. In this letter, new experimental spectra for $^{113,118–121}$Ag are presented and compared to those of the neighboring nuclei. The experimentally observed features, including signature splitting and inversion, are analyzed using large-scale shell-model calculations with a spherical basis and a simplified, two-orbital shell-model approach.

The $^{113–121}$Ag isotopes were populated using transfer-fission and fusion–fission induced by a ^{238}U beam at 6.2 MeV/u (with a typical intensity of 0.2 pnA), impinging on a 10-micron thick ^{9}Be target [27]. The experiment was performed at GANIL using the VAMOS++ [28] spectrometer and the EXOGAM array [29]. The large-acceptance spectrometer VAMOS++, placed at 20° with respect to the beam axis, was used to isotopically identify the fission fragments. The detection system of the spectrometer was composed of (i) a pair of multi-wire parallel plate avalanche counters (MWPPAC) at target and focal plane (time-of-flight (ToF)), (ii) two drift chambers (x, y, θ_f, ϕ_f), (iii) an ionization chamber with segmented structure (ΔE), and (iv) 40 silicon detectors (E_r). A typical resolution in mass and atomic number was $\Delta A/A \sim 0.4\%$ and $\Delta Z/Z \sim 1.7\%$ [20,28], respectively. The prompt γ rays were detected using the EXOGAM array in coincidence with the isotopically identified fission fragments. EXOGAM consisted of 11 Compton-suppressed segmented clover HPGe detectors, placed 15 cm from the target. The Doppler correction of γ-ray energy was carried out using the velocity vector of the fragment and corresponding angle of the clover segment. Typical uncertainties of γ-ray energies were $\sim$1 keV.

The newly observed level schemes of $^{113,118–121}$Ag were built based on the (i) coincidence between γ-ray transitions, (ii) relative intensities, and (iii) energy systematics of neighboring nuclides. The experimental setup is sensitive to the levels with lifetimes shorter than $\sim$2 ns due to the geometry of the Compton shielding. This restricts the observed transitions to multi-polarities E1, M1, and E2, since higher-order transitions are unlikely. From the systematics of the neighboring isotopes, the γ-ray transitions between adjacent levels in the Ag isotopes were assigned as $\Delta J = 1$.

The isotopically identified and Doppler corrected γ-ray spectra for odd-A ^{113,119,121}Ag and even-A ^{118,120}Ag are shown in Figs. 1 and 2, respectively. The γ–γ coincidence spectrum for each isotope is shown in the inset. The transitions that could not be placed in the level scheme due to lack of γ–γ coincidences are indicated by (#) and transitions assigned to the side bands are marked by (*).

The level schemes of odd-A ^{113,119,121}Ag are presented in Fig. 3(a). The level scheme of ^{113}Ag was built on the 43.7 keV $7/2^+$ long-lived isomeric state [30] using the systematics of odd-A Ag isotopes. The γ–γ coincidence spectrum gated on the 533 keV transition (side band) shows peaks at 430 and 95 keV, therefore