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In-beam γ ray spectroscopy of ^{94}Ag

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Abstract. The fusion evaporation reaction ^{40}Ca(^{58}Ni,p3n)^{94}Ag has been used to study the odd-odd N=Z nucleus ^{94}Ag at JYFL-ACCLAB using the MARA recoil separator and the JUROGAM 3 HPGe detector array. The recoil-β-tagging technique has allowed the observation of γ rays de-exciting states in ^{94}Ag for the first time. Shell model calculations using the JUN45 interaction including multipole and monopole electromagnetic effects are presented. Comparison with analog states observed in neighbor isobar nucleus ^{94}Pd is also discussed.

1 Introduction

The observation of similar behaviour of protons and neutrons under the strong nuclear force lead to the definition of isospin T, introduced by Heisenberg almost 100 years ago to account for the apparent charge independence of the nucleon-nucleon interaction [1]. However, if the nuclear interaction was actually the same for protons and neutrons, nuclear properties such as masses and excitation energies would depend only on the mass number A and therefore would be identical along an isobaric chain. Naturally, the Coulomb force will break this degeneracy, although the underlying wave functions are expected to retain their isospin symmetry.

Isospin symmetry implies that states with the same isospin T in mirror nuclei are remarkably similar. Energy differences between isobaric analog states arise from isospin-non-conserving interactions, such as Coulomb. In the last decades, many theoretical [2–6] and experimental [7–20] efforts have been devoted to studying the origin of these asymmetries. These studies have shown that electromagnetic effects alone cannot explain these energy differences, suggesting other effective isospin-non-conserving interactions are required to reproduce observations.

N~Z systems present the perfect testing ground to probe isospin symmetry phenomena. In particular, pairing correlations have a significant influence in the description of the nuclear structure of N=Z nuclei, where protons and neutrons are arranged occupying the same orbits, allowing the unusual T=0 neutron-proton (np) pairing in addition to the normal T=1 pairing mode. Despite experimental efforts, convincing evidence for the former pairing mode still evades observation and hence it remains an open question whether T=0 pairs bear any relevance in the nuclear structure of these nuclei. However, the much-discussed case of ^{92}Pd [21], where it was suggested that spin-aligned np pairs dominate the wavefunction of the y-rast sequence, prompted theoretical studies [22–24] devoted to probe the contribution of spin-aligned np pairs in other N=Z A >90 nuclei, such as ^{94}Ag and ^{96}Cd. These studies indicated the potential for significant contributions from T=0 np pairs in the wavefunctions of the yrast states in these nuclei.

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Many studies have been focused on ^{94}Ag [25–39]. Previous to this work, knowledge on ^{94}Ag was limited to the 0^+ ground state and two isomeric states (7^+) and (21^+) [27], whose half-lives are 27(2) ms [25, 26], 0.50(1) s [25, 28] and 0.39(4) s [28], respectively.

Here we report the first observation of γ rays between states in ^{94}Ag [20]. Experimental results will be discussed through comparison with analog states in ^{94}Pd and shell model calculations.

2 Experimental details

A ^{58}Ni beam was accelerated to 167 MeV by the K-130 cyclotron at the Accelerator Laboratory of the University of Jyväskylä. This beam, of 2.5 pnA, was used to bombard a 0.75 mg/cm^2 thick natural calcium target for 116h in order to populate states in ^{94}Ag via the p3n fusion-evaporation channel. The JUROGAM 3 germanium detector array, consisting of 15 single-crystal and 24 clover detectors and providing a total efficiency of 6 % at 900 keV [41], was used to detect prompt γ rays at the target position. Charged particles evaporated in the reaction were observed in the JYTube veto detector, comprising 96 plastic scintillators arranged in an hexagonal barrel around the target that offers 67% detection efficiency of a single proton [42]. The MARA mass spectrometer allowed mass-over-charge identification of the reaction products [43]. The separator was tuned to maximise transmission of A=94 recoils to the focal plane, where they passed through a multiwire proportional counter (MWPC) before implantation in a double-sided silicon strip detector (DSSSD) 300 μm thick and segmented in 192 vertical and 72 horizontal strips on the front and back sides respectively. A planar germanium detector placed behind the DSSSD allowed the observation of the β decay of the implanted recoils.

Signals from the aforementioned detectors were time stamped by a universal 100 MHz clock to enable time correlations between charged-particles, γ rays, recoils and decays. Hence events presenting coincident signals in both the DSSSD and MWPC are considered recoils while events recording a signal in the DSSSD with no energy deposited in the MWPC are deemed decays.

3 Method and analysis

Prompt transitions in ^{94}Ag were identified by requesting the observation of a short-lived A=94 recoil in coincidence with one or zero charged particles detected in the JYTube. The resulting Doppler corrected γ ray spectra is shown in figure 1a. Comparison with γ ray spectra recorded for recoils with longer decay times (figure 1b), higher charged particle multiplicity (figure 1c) and any A=94 recoil (figure 1d) show that 274(1), 463(1), 637(1), 791(1), 874(1), 1121(1) and 1148(1) keV γ rays appear to grow with respect other A=94 contaminants when gating on both the reaction channel leading to ^{94}Ag and a decay time consistent with the current lifetime of ^{94}Ag ground state. Two additional transitions at 581(2) and 648(2) keV also seem to increase in intensity, but they can only be deemed as tentative due to overlap with transitions in ^{94}Ru and ^{94}Rh.

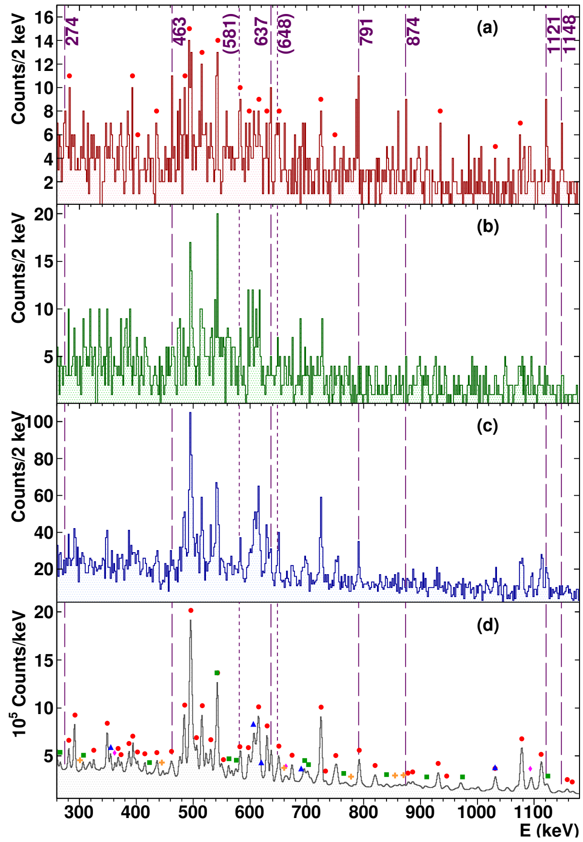

Figure 1. Prompt γ ray spectra of $A = 94$ recoils in coincidence with a high-energy β observed within (a) 60 ms or (b) between 120 and 180 ms from implantation. Events with 2 or more charged-particles detected in the JYTube were vetoed. Panel (c) shows same spectrum as (a) but with 2 or more charged particles were observed in the JYTube. The prompt γ ray spectrum for all $A = 94$ recoils is shown in (d). The ^{94}Ag transitions identified in this work are highlighted in red dashed lines. Symbols in (d) indicate transitions of known contaminants: ^{94}Ru (red circles), ^{94}Rh (green squares), ^{94}Tc (blue triangles), ^{94}Mo (pink diamonds) and ^{90}Mo (orange crosses) - see text for details. Adapted from [20].

States in ^{94}Ag were very weakly populated, with the estimated cross section being 450(100) nb (assuming 50% of the yield is lost on the isomers). The dominant channels were ^{94}Ru, ^{94}Rh, ^{94}Tc and ^{90}Mo (present due to a small overlap in the A/q selection), as shown in figure 1d). These contaminants produce the background in figure 1a), coming from either false correlations between recoil and decay events or, to a lesser extent, misidentified p3n events due to a missing proton in the JYTube.

Therefore the aforementioned γ rays can be associated with a short-lived β-decaying A=94 nucleus, produced via the one charged particle evaporation channel and whose half-life is consistent with the currently accepted value for the ^{94}Ag ground state β-decay. Hence these transitions can be considered the first observed γ rays from states in ^{94}Ag.

4 Discussion

The determination of the level scheme through γ-γ analysis was not possible due to the low statistics. Instead, we propose a tentative level scheme for the T=1 states in ^{94}Ag

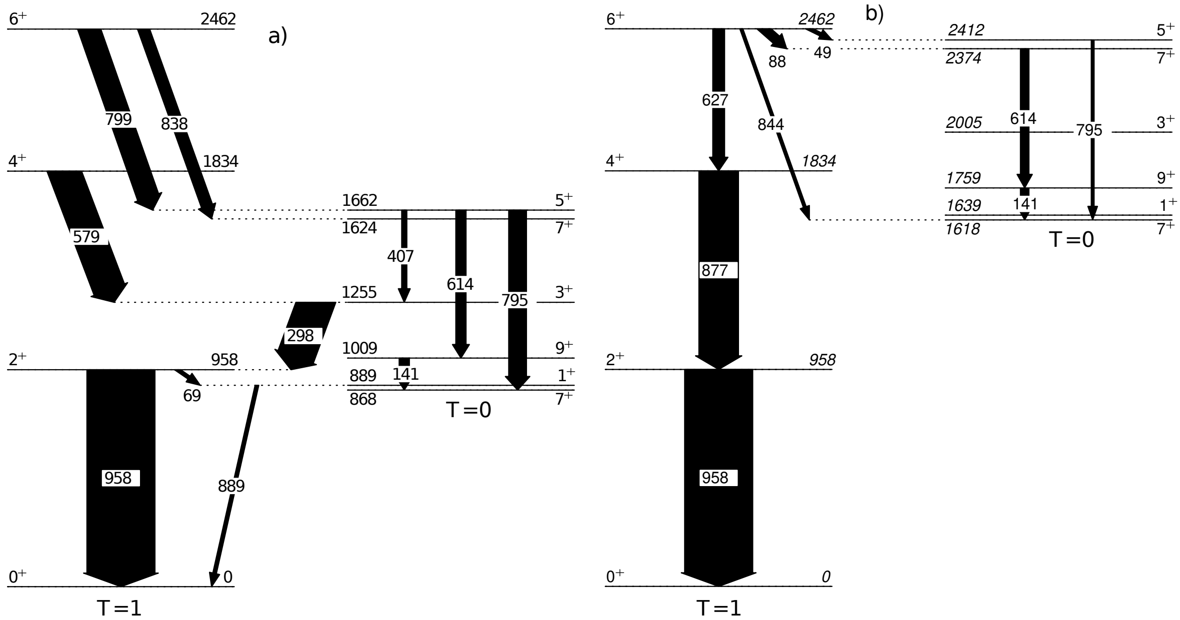

Figure 2. (Left) Theoretical ^{94}Ag decay scheme, predicted by shell-model calculations assuming direct population of only 2^+, 4^+ and 6^+ $T = 1$ states. (Right) Predicted decay path when the $T = 0$ states are shifted upwards by 750 keV. In both cases, only transitions with intensities higher than 4% are shown and states not involved in the de-excitation path are not depicted. Adapted from [20].

based on a comparison with the neighbouring T=1 isobar nucleus ^{94}Pd. Henceforth, we tentatively assign the 791, 874 and 637 keV γ rays as the analogs of the 814, 905 and 659 transitions corresponding to the yrast sequence from the 6^+ to the ground state in ^{94}Pd [44].

Shell model calculations were performed using the JUN45 interaction [45] in the fpg model space, taking into account Coulomb and magnetic monopole effects to modify single-particle energy levels according to [46]. The resulting wavefunctions were analysed to examine electromagnetic transitions from the $T = 1$ states up to 6^+ and all the $T = 0$ states that could be involved in the deexcitation path of those $T = 1$ states and deduce their transition strengths. For these calculations, effective charges of $\epsilon_p = 1.5$ and $\epsilon_n = 0.5$ and bare nucleon g-factors were considered. Assuming direct population with equal intensity, as one may expect in fusion evaporation reactions, of only the first three $T = 1$ excited states, namely 2^+, 4^+ and 6^+, we have produced the theoretical decay scheme of ^{94}Ag shown in Fig. 2(a). This prediction suggests that the $2^+ \rightarrow 0^+$ may be the only E2 transition observed, with higher lying T=1 states decaying through T=0 states via M1 transitions. However, if the T=0 states are shifted 750 keV towards higher energies, the E2 transition becomes the dominant deexcitation path for the $T = 1$ states up to 6^+ as shown in figure 2b). It is important to note that there is no evidence for the location of the $T = 0$ states, this is an illustrative exercise to highlight that these calculations rely on the assumption that the shell model succeeds in reproducing the energy difference between $T = 0$ and $T = 1$ states. Further work is required to determine relative position between $T = 0$ and $T = 1$ states, since it is strongly dependent on the np spin-aligned $g_{\frac{9}{2}}$ matrix element as demonstrated in [23].

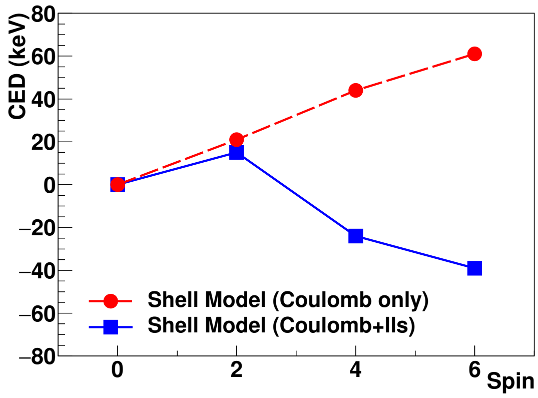

Figure 3. Theoretical Coulomb Energy Differences (CED) as a function of J between $T = 1$ analog states in ^{94}Ag and ^{94}Pd. Predictions with (blue squares) and without (red circles) single-particle monopole effects are depicted. Adapted from [20].

Most Coulomb energy differences (CED) present a positive trend [3, 18, 19] due to presence of $T = 1$ np pairs in the odd-odd $N = Z$ system as opposed to the $T = 1$ nn and pp pairs in the even-even neighbour [19], only for A=70 a negative trend has been observed before [18, 47]. Figure 3 shows in red circles the predicted CED for A=94 considering only two-body Coulomb (multipole) interaction added into the proton matrix elements, presenting the common positive trend. However, the inclusion of single-particle monopole effects due to Coulomb and magnetic shifts in single-particle levels (shown in blue squares and labelled as lls [2]) yields a negative trend after 2^+ as CEDs for $J^\pi = 4^+, 6^+$ become negative. Although we previously proposed 791, 874 and 637 keV transitions in ^{94}Ag as tentative candidates for the E2 transitions from the 6^+ to the ground-state based on comparison with ^{94}Pd, we do not have definitive evidence to make this claim and therefore the experimental CED are not shown in figure 3. However, previous shell model analysis suggests the $2^+ \rightarrow 0^+$ transition is among those observed in this work. The 791 keV remains the most likely candidate for this assignment, leading to a CED value of -22 keV. If 874 and 637 keV were to follow as the next E2 transitions from the 4^+ and 6^+ states in ^{94}Ag a smooth negative trend would emerge. Clearly, further experimental work is required in order to test the predictions of the shell model.

5 Summary

Nine γ rays (2 tentative) have been observed in this work in coincidence with a short-lived β-decaying $A = 94$ nucleus produced via a one-charged particle evaporation channel in the ^{40}Ca+^{58}Ni reaction and whose half-life is consistent with the currently accepted value for the ^{94}Ag ground state. They represent the first observation of γ rays from ^{94}Ag excited states. Isospin symmetry arguments were used to discuss possible correspondence between some of the observed transitions and those observed between states in ^{94}Pd. Shell-model calculations, including multipole and monopole electromagnetic effects, have been presented and used to deduce theoretical CED up to $J = 6$. These calculations have also shown that the intensities of any observed E2 transitions are strongly influenced by the relative position of $T = 0$ and $T = 1$ states. Locating the $T = 0$ states in this nucleus may provide insight into the strength of the $g_{\frac{9}{2}}$ np spin-aligned matrix element and therefore further work is required to determine the level scheme of ^{94}Ag.

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