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Short Note

Evidence for excited states in ^{95}Ag

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Abstract. The first evidence for excited states in ^{95}Ag is presented. ^{95}Ag is the heaviest $T_z = 1/2$ nucleus for which gamma-rays have been identified. The reaction ^{40}Ca(^{58}Ni, 1p2n)^{95}Ag was used in the experiment, which resulted in the assignment of three gamma-rays to ^{95}Ag. A detector system consisting of the detector arrays Euroball, Neutron Wall and Euclides was used to detect gamma-rays, neutrons and charged particles, respectively.

PACS. 23.20.Lv Gamma transitions and level energies – 25.70.Gh Compound nucleus – 27.60.+j $90 \leq A \leq 149$

1 Introduction

Nuclei at and close to the $N = Z$ line have received an increased attention in recent years when new techniques have allowed studies of heavier and heavier nuclei around the $N = Z$ line. In these nuclei, neutrons and protons occupy largely the same orbitals, and for heavier $N \approx Z$ nuclei, approaching ^{100}Sn, new effects resulting from neutron-proton (n-p) interactions may be expected. One possibility is the occurrence of a new mode of pairing interactions where n-p pairs coupled to either $T = 0$ or $T = 1$ extend the more common $T = 1$ like particle pairing correlations observed for nuclei closer to stability. However, unexpected structural effects may also arise due to the residual interactions of neutrons and protons in single-particle orbits near closed shells. The region of nuclei immediately below the doubly magic nucleus ^{100}Sn with $N < 50$, $Z < 50$ is here of special interest. The high-degeneracy $g_{9/2}$ shells of neutrons and protons dominate the structure of these nuclei. The strong attraction in the aligned 9^+ coupling of a neutron hole and a proton hole will have a dramatic effect on the nuclear coupling scheme. The seniority coupling scheme is expected to break down already in the 0^+ ground state of ^{96}Cd with two neutron holes and two proton holes. Instead, the coupling scheme in this state is expected to come close to an aligned coupling scheme, *i.e.* a situation where two neutron-proton hole pairs each couple to 9^+ and the two pairs combine to give the total angular momentum 0. In this arrangement the angular-momentum vectors of all four nucleon holes are aligned parallel or anti-parallel to each other, resulting in a large intrinsic quadrupole moment. Another consequence of the strong neutron-proton attraction in aligned configurations is the expected appearance of spin-gap isomerism [1] in several nuclei in the $N < 50$, $Z < 50$ region. Such a long-lived isomer has been found in ^{95}Pd [2] ($21/2^+$, $T_{1/2} = 14$ s). Similar spin traps are expected in, *e.g.*, ^{95}Ag ($23/2^+$), ^{96}Cd (16^+) [3] and ^{97}Cd ($25/2^+$).

The advent of large Ge-detector arrays and their coupling to efficient ancillary detectors for evaporated particles and evaporation residues in heavy-ion fusion reac-

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tions have enabled significant progress in the exploration of nuclei along the $N = Z$ line. The doubly magic self-conjugate nucleus ^{100}Sn is the heaviest $N = Z$ nucleus expected to be bound and therefore sets a natural limit for these experimental efforts. However, when approaching ^{100}Sn the population cross-sections decrease dramatically (and ^{100}Sn itself is most probably only accessible via the next generation of intense radioactive beams). In this work we present evidence for the observation of gamma-rays depopulating excited states in the $T_z = 1/2$ nucleus ^{95}Ag which is characterized by three proton holes and two neutron holes outside the ^{100}Sn core.

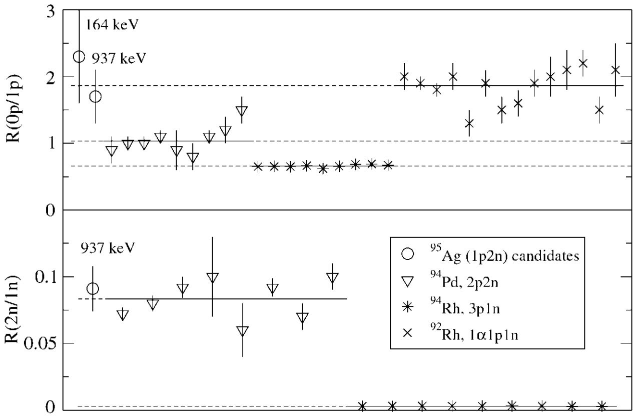

Fig. 1. The top panel shows the intensity ratio of different gamma-rays deduced from spectra gated by zero protons and one proton, respectively. The bottom panel shows a similar ratio obtained from spectra gated by two neutrons and one neutron. The same quantities, measured for known transitions in the nuclei ^{94}Pd [7,8], ^{94}Rh [9] and ^{92}Rh [10] have been included for comparison. The ratios for ^{94}Pd and ^{92}Rh have been deduced from spectra additionally gated by known gamma-rays in these nuclei.

2 Experimental procedure

The experiment was performed at the Institut de Recherches Subatomiques in Strasbourg, France, using the fusion evaporation reaction ^{40}Ca(^{58}Ni, 1p2n)^{95}Ag. The pulsed ^{58}Ni beam had an energy of 208 MeV, a repetition frequency of 3 MHz, and the duration of each beam pulse was 4.4 ns. The target foil consisted of 1 mg/cm^2 highly enriched ^{40}Ca on a 15 mg/cm^2 gold backing. Gamma-rays emitted in the reaction were detected using the Euroball [4] Ge-detector array, then consisting of 15 cluster and 26 clover detectors. These are composite detectors, each comprising 7 and 4 germanium crystals, respectively. Each composite detector is surrounded by a BGO anti-Compton shield. Neutrons and charged particles were detected in coincidence with the gamma-rays, using the Neutron Wall [5] and the charged-particle detector array Euclides [6]. The Neutron Wall comprised at the time 37 liquid scintillating detectors placed at forward angles, relative to the beam. The Euclides array consisted of 40 ΔE-E silicon telescope detectors, of which 5 were divided into 4 segments.

The event trigger required that at least one escape-suppressed gamma-ray had been detected in coincidence with at least one neutron (as identified by a hardware gate in the Neutron Wall electronics), or that at least three escape suppressed gamma-rays had been detected in coincidence. During three days of irradiation time with an average beam intensity of 3 pnA, of the order of $6 \cdot 10^8$ raw gamma-ray events fulfilling either of these trigger conditions were collected by the data acquisition system and stored on a magnetic tape for later off-line analysis. After add-back, *i.e.* summing the energy contributions of Compton-scattered gamma-rays from different segments of a composite detector, the gamma-rays were sorted off-line into neutron and charged-particle–gated singles energy spectra and E_γ-E_γ coincidence matrices.

Conservative gating conditions were used for protons and alpha-particles, which resulted in efficiencies for detecting and correctly identifying these particles of around 36% for protons and 22% for alpha-particles.

The information provided by the Neutron Wall detectors includes a zero cross-over and a time-of-flight parameter. The time of flight is measured relative to the time reference of the event, and will be different for neutrons and gamma-rays detected by the Neutron Wall, due to the relatively large distance (51 cm) from the target to the front faces of the neutron detectors. The time reference can be provided by the Neutron Wall, which has excellent time resolution, but this makes it more difficult to distinguish between neutrons and gamma-rays, since events where no gamma-ray is detected in the Neutron Wall will have a different type of time reference from the more common case where a gamma-ray was detected before any neutron hits the Neutron Wall. Furthermore, events where no gamma-rays or neutrons are detected in the Neutron Wall will be lost if this type of time reference is used. In order to avoid these problems, a pulsed beam was used in the present experiment, and the time reference of each event was given by the radio frequency signal of the beam pulsing system. In addition, conservative gating conditions were applied to the time of flight and zero cross-over parameters of the data in order to further reduce the number of gamma-rays misidentified as neutrons. Special care was taken to reduce the probability for a neutron scattering between two detectors of the Neutron Wall to be counted twice. This was done by always counting two simultaneous neutron-like events in neighboring Neutron Wall detectors as one neutron, and by gating on the time difference between the detection of two neutrons in non-adjacent detectors [11]. The resulting efficiency for detection and identification of the second neutron of a true two-neutron event was then 16%. The efficiency for detecting only one neutron could not be obtained from the data of the present experiment, since events in which a neutron has been detected were enhanced by the trigger conditions of the data acquisition system, relative to events without detected neutrons. However, this efficiency is typically around 25-30% [5], depending on the reaction kinematics. This number is reduced when the scattering between Neutron Wall detectors is taken into account.

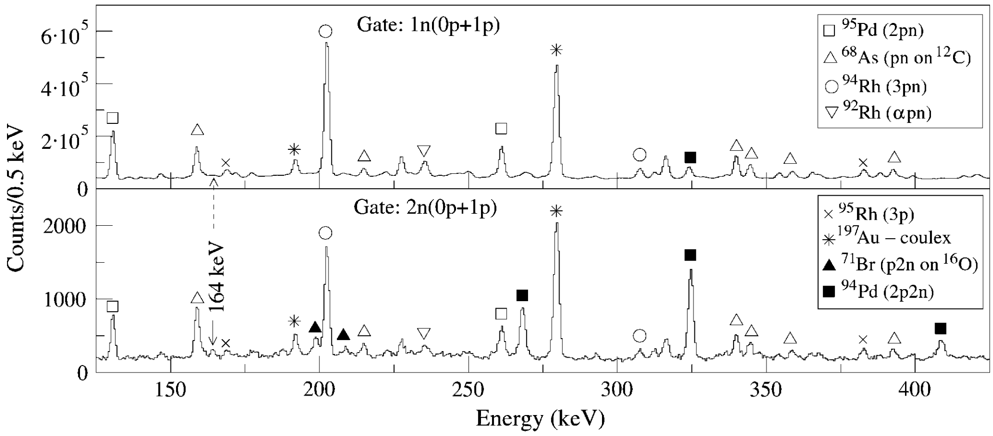

Fig. 2. The top panel shows the sum of a gamma-ray spectrum gated by zero protons and one neutron and a spectrum gated by one proton and one neutron. The bottom panel shows a similar spectrum which is the sum of spectra gated by two neutrons and zero or one proton, respectively. The energies and reaction channels of some peaks in the spectra are also indicated [12,10,7–9, 13,14], including gamma-ray peaks from ^{71}Br and ^{68}As, resulting from the reactions ^{16}O(^{58}Ni, p2n)^{71}Br and ^{12}C(^{58}Ni, pn)^{68}As with contaminants in the target.

3 Experimental results

A search for gamma-ray transitions depopulating excited states in ^{95}Ag was done by comparing the intensities of gamma-rays in spectra gated by different particle numbers. Two gamma-rays, with energies 164 and 937 keV, were assigned to ^{95}Ag in this manner in the present experiment, and a gamma-ray with the energy 1117 keV was tentatively assigned to the same reaction channel, mainly on the basis of coincidence relations.

The ^{40}Ca targets used in the experiment were contaminated by small amounts of ^{12}C and ^{16}O. Some small amounts of oxygen (oxide) contamination is inevitably left from the target production process. However, residual compounds in the evacuated target chamber may easily deposit on or react with the target, which is at a high temperature due to the beam bombardment. In the experiment this well-known effect, which leads primarily to ^{16}O and ^{12}C contamination, was minimized by switching targets at regular intervals. The reaction products from the ^{58}Ni beam bombardment on these contaminants are known, and the corresponding gamma-rays could be identified. A comparison was also made with spectra from a previous experiment [12], in which a ^{58}Ni beam and a ^{12}C target was used. The gamma-rays assigned to ^{95}Ag were not present in these spectra.

The ratio between the intensities of a gamma-ray transition measured in spectra gated by different combinations of particles depends on the detection efficiencies for the particles and on the reaction channel of the specific gamma-ray, *i.e.* on the number of particles that were emitted in coincidence with it. In fig. 1 such intensity ratios are shown for the gamma-rays assigned to ^{95}Ag and for some known transitions from other reaction channels, which have been included for comparison. The topmost panel shows the intensity ratio of gamma-rays in spectra gated by zero protons and one proton, respectively, and the bottom panel shows a similar ratio obtained from spectra gated by two neutrons and one neutron. The ratios for the 937 keV transition were obtained by first subtracting a fraction of spectra gated by the αpn reaction channel (^{92}Rh [10]), where a contaminating transition is present. For the 164 keV transition it was, due to contaminants of similar energy, not possible to measure the intensity of the peak in spectra gated by only one neutron. Nevertheless, the spectra in fig. 2 show that the 164 keV gamma-ray qualitatively exhibits the same behavior as known gamma-rays from 2n reaction channels, as indicated in the figure.

A gamma-ray spectrum resulting from a gate on two neutrons, zero or one proton, and the 164 keV gamma-ray is shown in the bottom panel of fig. 3. In the top panel, a background spectrum has been included for comparison. This spectrum was produced using the same particle gate conditions together with a gamma-ray “background” gate applied to a wide energy range below 164 keV, chosen to include few known transitions. The 937 keV gamma-ray is visible in the spectrum gated on 164 keV, as well as gamma-rays from the strongest one and two-neutron channels (^{94}Rh and ^{94}Pd) of the experiment. A peak is also visible at the energy 1117 keV. This gamma-ray does indeed appear to be produced in the p2n reaction channel, judging from the particle-gated spectra, but the intensity of this gamma-ray was significantly lower than those of the 937 and 164 keV gamma-rays. Therefore, and due to contaminants with energies close to 1117 keV, it was not possible to establish intensity ratios for this transition, and its assignment to ^{95}Ag therefore chiefly rests on its being in coincidence with the 164 keV gamma-ray. The 937 and 1117 keV transitions have approximately equal intensity in this spectrum, even though the total intensity of the 937 keV transition is significantly higher, as can be seen in table 1. The table shows the relative intensities of the three gamma-rays assigned to ^{95}Ag, after the subtraction of contaminants. The 937 keV transition has the highest intensity of these gamma-rays. Based on the assumption that all ^{95}Ag nuclei created in the experiment decay

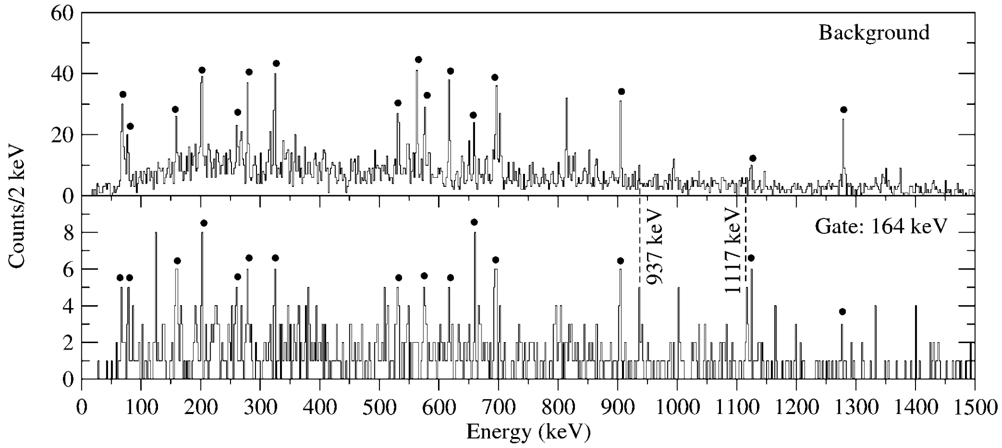

Fig. 3. The bottom panel shows a gamma-ray spectrum which has been produced by gating on two neutrons, zero or one proton, and the 164 keV gamma-ray. The top panel is a background spectrum produced by gating on the same particle numbers and a wide region of gamma-ray energies below 164 keV. Gamma-ray peaks from the strongest one and two-neutron reaction channels (^{94}Rh and ^{94}Pd) are visible in both spectra. Peaks present in both spectra are indicated by a solid circle. The dashed lines mark the peaks at 937 and 1117 keV. The unmarked peaks are most likely in coincidence with a different particle number than 1p2n.

Table 1. The energies and relative intensities of the three gamma-rays assigned to ^{95}Ag. Estimated uncertainties are given within parentheses. The 1117 keV transition is tentative.

Energy	Relative intensity
163.5(3)	59 (10)
936.6(2)	100 (18)
1116.9(8)	27 (13)

by emitting this gamma-ray, the experimental production cross-section was estimated to be of the order of 1 μb.

The lowest-lying $\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$ or $2^+ \rightarrow 0^+$ transition has an energy around 900 keV in the heaviest known $N = 48$ isotones. In combination with the 937 keV transition having the highest intensity of the gamma-rays assigned to ^{95}Ag in this work, this might suggest that the 937 keV transition is the $\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$ transition to the ground state in this nucleus. It is, however, difficult to interpret the three gamma-rays theoretically due to the lack of statistics.

4 Summary and conclusions

The first evidence for excited states in ^{95}Ag was presented. Two gamma-ray transitions, with the energies 164 and 937 keV, were assigned to this nucleus by means of comparison of gamma-ray spectra gated by different numbers of detected particles. A third gamma-ray, with the energy 1117 keV, was tentatively assigned to the same nucleus, chiefly based on its being in coincidence with the 164 keV transition. ^{95}Ag is the heaviest $T_z = 1/2$ nucleus for which evidence for excited states have been found.

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