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Study of the (21^+) isomer in ^{94}Ag

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Abstract. The experimental decay properties of the (21^+) isomer in ^{94}Ag are briefly discussed.

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Spin-gap isomers near doubly closed shell nuclei offer the chance to measure properties of single-particle states and to thus test predictions of the nuclear shell model [1]. An example is the $(7^+,9^+)$ isomer in ^{94}Ag, which was found [2] in a β-delayed proton study to have a long half-life of 0.42(5) s, the spin/parity assignment being based on a comparison with shell model predictions. This as well as follow-up experiments [3,4,5,6], which narrowed the assignment down to (7^+) and gave evidence for the existence of a second long-lived isomer in ^{94}Ag with a (21^+) assignment, were performed at the on-line mass separator [7] of GSI Darmstadt. The status of the research on the (21^+) isomer will be reviewed in this paper.

The ^{94}Ag nuclei were produced by ^{58}Ni(^{40}Ca, p3n) fusion-evaporation reactions, stopped in a catcher inside the ion source of the on-line mass separator and released as singly charged ions. In the experiments considered here [3,4,5,6] a FEBIAD-E or FEBIAD-B2C ion source, respectively, was used [8,9]. The latter one was equipped with cold pockets which enabled one to reach a beam intensity of 2 atoms/s for the long-lived ^{94}Ag isomers while suppressing the ^{94}Pd contamination. The mass-separated $A = 94$ beam was implanted into a tape which was positioned in the center of an array of charged-particle and γ-ray detectors and was regularly removed from the measuring position in order to avoid build-up of long-lived daughter activities. Originally we used a plastic scintillator for recording positrons and 12 germanium crystals for performing γ-ray spectroscopy in high resolution [3]. In the more recent measurements [4,5,6], three silicon-strip detectors were used for the former and 17 germanium crystals for the latter purpose. Moreover, the properties of the ^{94}Ag isomers were studied [6] by mean of a total absorption spectrometer [10].

The following decay properties have been ascribed to the (21^+) isomer in ^{94}Ag:

– By observing feeding of known [11] high-spin states in ^{94}Pd in β-γ-γ measurements [3], the existence of the higher-lying isomer was shown and a lower limit of 17 was deduced for its spin.
– Improved β-γ-γ data [4], obtained by using the silicon detectors for recording positrons, allowed us to extend the ^{94}Pd level scheme up to the (20^+) level at 7700 keV. The experimental ^{94}Pd level energies are in very good agreement with predictions of an empirical shell model. However, a large-scale shell model calculation is required to lower the 21^+ yrast state in ^{94}Ag below the 19^+ one, thus making the former an E4 spin-gap isomer. Based on this calculation, a tentative spin-parity assignment of (21^+) for the higher-lying of the two isomers in ^{94}Ag and a value of 6300 keV for its excitation energy were deduced. An upper limit of 10% was found for the branching ratio of the internal de-excitation of the (21^+) isomer.

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– By gating on high-energy events recorded in the silicon detectors, the β-delayed proton decay of the (21^+) isomer was investigated [5]. States in ^{93}Rh were found to be populated up to a $(33/2^+)$ level at 4708 keV and a $(39/2^- \text{-} 47/2^-)$ level at 6858 keV, whose properties are partially known from in-beam work [12]. These results confirm the existence of the (21^+) isomer. The half-lives of the (7^+) and (21^+) isomers were re-determined with improved accuracy to be 0.61(2) and 0.39(4) s, respectively. The total-absorption data confirmed the existence of two long-lived activities of ^{94}Ag, characterized by distinctly different β-endpoint energies, and showed that the (21^+) isomer is populated with a fraction of about 10 % of their total reaction yield.
– Beta-delayed two-proton decay of the ^{94}Ag isomers was searched for by gating on low-lying γ transitions in ^{92}Ru. In a preliminarily data analysis, a few events of this type have been registered [6] in proton-γ-γ coincidences for the 865 and 990 keV γ-transitions in ^{92}Ru [13], corresponding to a branching ratio of 0.2(2)% for β-delayed two-proton emission.
– Evidence for direct proton decay of the (21^+) isomer was obtained by demanding coincidences between single-hit events recorded in the silicon and γ-γ coincidence events observed in the germanium detectors [6]. The latter trigger was based on the known ^{93}Pd scheme [14]. The decay proton spectrum has a fine structure indicating two proton peaks 0.79(3) and 1.01(3) MeV. From these data, the excitation energy of the (21^+) isomer was found to be 6.6(3) MeV, assuming a proton separation energy of 0.89(5) MeV for ^{94}Ag [15].
– Finally, a fourfold coincidence condition was used between double-hit events in the silicon and γ-γ correlations in the germanium detectors, the latter ones being based on the known ^{92}Rh scheme [16]. In this way, preliminarily evidence for direct two-proton radioactivity of the (21^+) isomer was deduced, the two-proton sum energy amounting to 1.7(1) MeV [6].

These results are characterized by several exceptionally interesting features:

– An important prerequisite for the success of this work was the excellent release properties of the FEBIAD sources with sinter-graphite catchers for short-lived silver isotopes, which has also lead to the identification of $(23/2^+)$ and $(37/2^+)$ isomers in ^{95}Ag, their upper half-life limits being 16 and 40 ms, respectively [17].
– The fusion-evaporation reactions used in our work appear to exclusively populate high-spin levels but not the ground state of ^{94}Ag. The latter one has most probably a 0^+ assignment as can be deduced from the short half-life of $28(^{+29}_{-10})$ ms [18] which was obtained by using fragmentation reactions and indicates superallowed Fermi decay.
– For the case of the β-delayed and direct two-proton radioactivity of the (21^+) isomer in ^{94}Ag, the detection sensitivity corresponds to partial fusion-evaporation cross sections of about 140 and 350 pb, respectively. This sensitivity level is considerably below that reached in searching for decay properties of ^{100}Sn [19].
– The potential of decay spectroscopy of the (21^+) isomer can be seen from the fact that the high-spin schemes of ^{94}Pd, ^{93}Pd and ^{93}Rh have been improved compared to those obtained previously by in-beam spectroscopy.
– To our knowledge this work represents the first successful attempt to use multiple γ-γ coincidences to "tag" direct proton and two-proton emission. This technique is routinely used in studies of β- or γ-delayed charged-particle emission (see [20] for a recent work on the latter disintegration mode). However, it has not been applied to study direct proton or two-proton radioactivity, except for the search for charged particle-γ anti-coincidence events in the latter case [21].

All in all, we have identified a (21^+) isomer in ^{94}Ag, the heaviest odd-odd $N = Z$ nucleus with known decay properties. This isomer represents an unprecedented nuclear state in the entire Segré chart. It features a high excitation energy of 6.6(3) MeV, a short half-life of 0.39(4) s and no less than five decay modes, *i.e.* β-delayed γ-ray, proton and two-proton emission as well as direct proton and two-proton radioactivity. In particular, the direct emission of protons and two-protons from the same long-lived nuclear state is a unique phenomenon. Thus we have very good reasons to call ^{94m}Ag (21^+) a truly exotic nuclear state.

It is a challenge to future experiments to, firstly, confirm the existence of the two-proton radioactivity of ^{94m}Ag (21^+) by accumulating better counting statistics for proton-proton-γ-γ events and, secondly, measure the angular correlations between the two protons and to thus clarify the emission process. Compared to such measurements of other cases of two-proton decay (see [21] for a recent review), ^{94m}Ag (21^+) samples prepared by means of an on-line mass separator offer a triple advantage: They are of high purity and comparatively large source strength and allow one to distinguish proton and two-proton radioactivity by means of γ-γ coincidence tagging.

References

1. H. Grawe *et al.*, these proceedings.
2. K. Schmidt *et al.*, Z. Phys. **350**, 88 (1994).
3. M. La Commara *et al.*, Nucl. Phys. A **708**, 167 (2002).
4. C. Plettner *et al.*, Nucl. Phys. A **733**, 20 (2004).
5. I. Mukha *et al.*, Phys. Rev. C **70**, 044311 (2004).
6. I. Mukha *et al.*, submitted to Phys. Rev. Lett.
7. E. Roeckl *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 53 (2003).
8. R. Kirchner, Nucl. Instrum. Methods Phys. Res. B **26**, 204 (1987); **204**, 179 (2003).
9. R. Kirchner, Nucl. Instrum. Methods Phys. Res. B **70**, 186 (1992).
10. M. Karny *et al.*, Nucl. Instrum. Methods Phys. Res. B **126**, 411 (1997).
11. M. Górska *et al.*, Z. Phys. **353**, 233 (1995).
12. H. A. Roth *et al.*, J. Phys. G **21**, L1 (1995).
13. C. M. Baglin, Nucl. Data Sheets **81**, 423 (2000).
14. C. Rusu *et al.*, Phys. Rev. C **69**, 024307 (2004).
15. G. Audi *et al.*, Nucl. Phys. A **729**, 337 (2003).

16. D. Kast *et al.*, Z. Phys. **356**, 363 (1997).
17. J. Döring *et al.*, Phys. Rev. C **68**, 034306 (2003).
18. A. Stolz *et al.*, in *Proceedings of the International Workshop on Selected Topics on N=Z Nuclei (PINGST 2000), Lund, Sweden 2000*, edited by D. Rudolph, M. Hellström (Lund University, Lund Institute of Technology, Lund, Sweden, 2000), LUIP 003, p. 113.
19. M. Karny *et al.*, these proceedings.
20. D. Rudolph *et al.*, Phys. Rev. Lett. **350**, (1994) 88.
21. M. Pfützner *et al.*, these proceedings.