ONE-PROTON AND TWO-PROTON RADIOACTIVITY OF THE (21^+) ISOMER IN ^{94}Ag*

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The properties of the (21^+) isomer of ^{94}Ag, unprecedented in the entire nuclear chart, are presented with particular emphasis on its hindered one-proton and enhanced two-proton radioactivity. The tasks emerging from these results concerning experimental and theoretical efforts are discussed.

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1. Introduction

The (21^+) isomer occurring in the lightest known isotope of silver, ^{94}Ag, has properties that are unmatched in the entire nuclear chart. It is characterised by a long half-life of 0.39(4) s [1], a high spin [2] and a high excitation energy of 6.7(5) MeV [3] which, although the dominant disintegration modes are β-delayed γ-ray [2] or proton [1] emission, makes direct one-proton ($1p$) and two-proton ($2p$) radioactivity possible. The experimental results on the

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latter two decay modes [3, 4] will be briefly summarised here and an outlook will be given on the experimental and theoretical tasks if not challenges emerging from these data.

2. Experimental technique

The decay properties of the (21^+) isomer were studied at the GSI on-line mass separator by using a ^{58}Ni(^{40}Ca$, p3n$) fusion-evaporation reaction. After ionisation and acceleration to 55 keV, the $A = 94$ ions were mass separated and implanted into a tape positioned in the centre of an array of segmented silicon and composite germanium detectors. The tape was periodically removed from the implantation position in order to reduce the build-up of long-lived daughter activity. While the silicon detectors were used to record protons the germanium crystals served to 'tag' on known γ-ray transitions in the $1p$ daughter, ^{93}Pd [5], and the $2p$ daughter, ^{92}Rh [6], respectively.

3. Experimental results and discussion

By using the γ-tagging method the $1p$ and $2p$ radioactivity was identified, the decay energies and decay probabilities amounting to 0.79 MeV, 1.01 MeV and 1.9(5)%, 2.2(4)% in the former and 1.9(1) MeV and 0.5(3)% in the latter case. The resulting level schemes are shown in Figs. 1 and 2, respectively. The cross-section for producing the $2p$ radioactivity in the fusion–evaporation reaction was found to be about 350 pb, averaged over the 2.6 mg/cm^2 thick ^{58}Ni target [8].

By comparing the experimental partial half-lives of the two $1p$-decay modes with WKB estimates, very small spectroscopic factors of 1×10^{-6} and 3×10^{-7} were deduced [3]. Such a large hindrance quantitatively agrees with that obtained when considering the other two known cases of proton emission from high-spin isomers, ^{53m}Co $(19/2^-)$ [9] and ^{54m}Ni (10^+) [10].

The experimental proton–proton correlation data are displayed in Fig. 3 together with predictions obtained from the break-up model (see [4] and references therein). The correlation spectra were derived out of the Si1–Si2–γ–γ coincidence matrix, with a total of 19 events fulfilling the triple condition set on two ^{92}Rh γ-transitions and on the $2p$ sum-energy in the range of 1.8–1.95 MeV.

In general, $2p$ decay can proceed through sequential proton emission involving intermediate ^{93}Pd states, or through a simultaneous three-particle decay mechanism. The former decay should result in narrow peaks in the spectrum shown in Fig. 3(b) whose energies depend on the (unknown) energy of the ^{92}Rh state involved and should add up to a total of 1.9(1) MeV. As

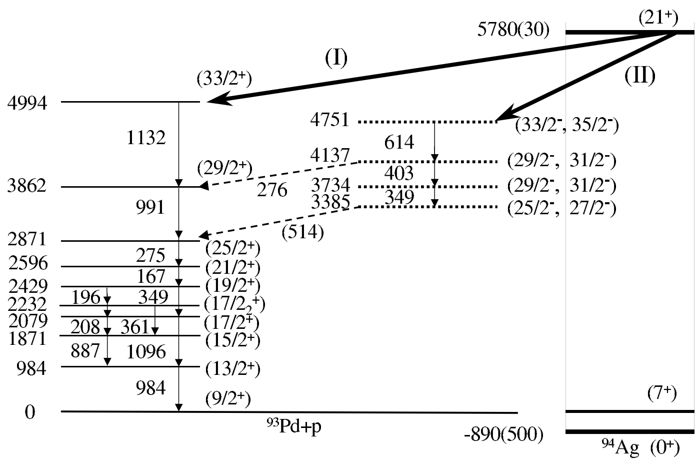

Fig. 1. One-proton decay of the (21^+) isomer of ^{94}Ag to excited states in ^{93}Pd. Energies of γ transitions and levels in ^{93}Pd are given in keV, the latter ones with respect to the $^{93}\mathrm{Pd} + p$ threshold [3]. The energy of the ^{94}Ag ground-state and the proton separation energy in this nucleus stem from the recent atomic mass evaluation [7]. All spin assignments are tentative, being based on both decay [1–3] and in-beam [5] work (from [4]).

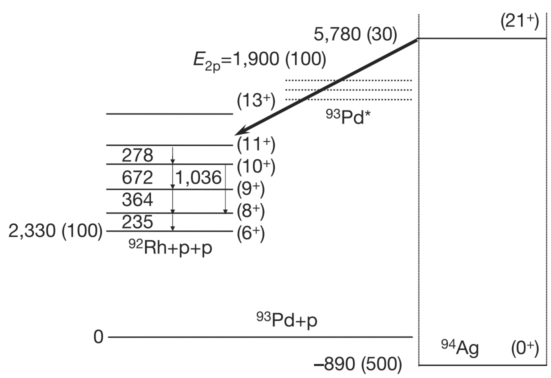

Fig. 2. Two-proton decay of the (21^+) isomer of ^{94}Ag to excited states in ^{92}Rh. All level energies are given with respect to the ^{93}Pd ground-state. Energies of γ transitions and levels in ^{93}Pd and the excitation energy of the (21^+) isomer are in keV. The triple dotted line indicates excited states of ^{93}Pd that might be involved in sequential $2p$ decay. On the far left side, the proton separation energy in ^{93}Pd is indicated as tentatively assigned in [4]. The energy of the ^{94}Ag ground-state stems from the recent atomic mass evaluation [7]. All spin assignments are tentative, being based on both decay [1–4] and in-beam [6] work (from [3]).

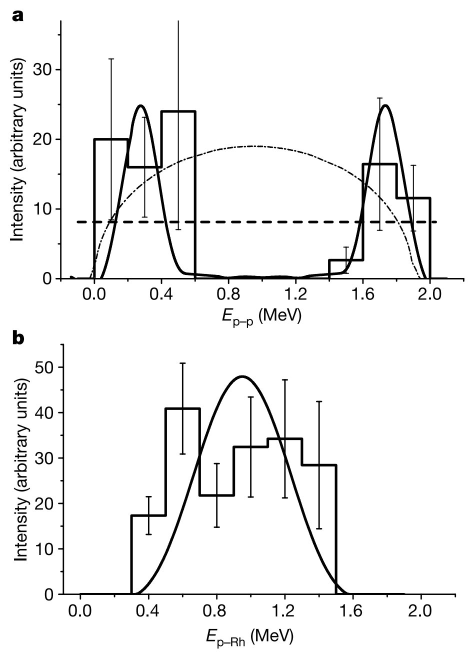

Fig. 3. Correlations observed in the $2p$ decay of the (21^+) isomer of ^{94}Ag. Relative-energy spectra for proton–proton (E_{p-p}) and proton-^{92}Rh ($E_{p-\mathrm{Rh}}$) correlations are shown by histograms in (a) and (b), respectively. The solid curves are the predictions of our model of simultaneous proton emission from a deformed nucleus convoluted with an experimental uncertainty of 200 keV. The dashed line represents the fit obtained with a sequential emission mechanism. The dashed-dotted curve shows the calculated distribution when the $2p$ decay is isotropic in the absence of the mentioned decay mechanisms (from [3]).

there is no evidence for such peaks (see Fig. 3(b)), the observed proton-proton correlations seem to be consistent only with ^{94}Ag decaying through a simultaneous $2p$ emission process. For ^{94}Ag such a 'true' $2p$-decay is expected to be much slower than the sequential decay mode. However, the $2p$-decay half-life estimated by using the 'simultaneous emission' model exceeds the corresponding experimental result by a factor of 10^3–10^6 (see Fig. 4). Hence, the $2p$-decay is *enhanced* in contrast to the $1p$-decay which, as mentioned above, is *hindered*.

The experimental results on the $2p$ half-life is interpreted, on the basis of a comparison with predictions from the breakup model, as indicating a very large, prolate deformation of the parent nucleus, with the emission of protons occurring either from the same or from opposite ends of a 'cigar'-shaped nucleus [4] (see Fig. 4).

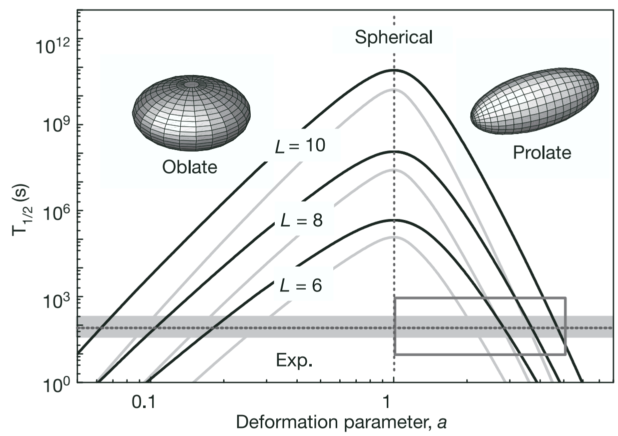

Fig. 4. Nuclear deformation of the (21^+) isomer of ^{94}Ag derived from its two-proton decay. The partial $2p$-decay half-life, $T_{1/2}$, is plotted as a function of the nuclear deformation parameter a, which is the ratio of the long to the short axes of an ellipsoid. The simultaneous (black curves) and quasi-classical ^{2}He (grey curves) model estimates of the 2p decay are shown for the angular momenta $L = 6, 8, 10$. The nuclear shapes corresponding to the derived deformations are shown for the $L = 6$ calculation. The $T_{1/2}$ value is shown by the dotted line (marked as "Exp.") with the grey region of experimental uncertainty (from [3]).

4. Summary and outlook

Comparing the results on ^{94m}Ag (21^+) presented in Refs. [3, 4] with the published literature we conclude that it is the first time that $1p$ and $2p$ radioactivity has been identified to occur from one and the same nuclear state and it is the first time that proton–proton correlations have been observed in $2p$ radioactivity. There is a twofold puzzle emerging from these data. Firstly, the $1p$ decay is hindered while proton–proton correlations indicate of collinear or back-to-back emission of the two protons, which is interpreted, on the basis of the breakup model, as indicating strong deformation of the isomer. These results represent indeed a challenge for future studies concerning both theory and experiment.

As far as theory is concerned, it was recently shown that a cranked Nilsson–Strutinski approach predicts a very large microscopic energy for the lowest-lying 21^+ state of ^{94m}Ag, yielding agreement with the experimental isomer energy [11]. However, the shape of this state, resulting from $\pi(g_{9/2})^{-3} \times \nu(g_{9/2})^{-3}$ coupling, is predicted to be close to spherical while a deformation with a 2:1 axis ratio is calculated to occur at an higher excitation that is more than 10 MeV energy higher. The close to spherical shape of the lowest lying 21^+ state of ^{94m}Ag is also expected [12] on the basis of the large-basis shell model calculations that reproduce [2, 12] the inversion of the 19^+ and 21^+ level, thus explaining the observed isomerism of the latter state. Hence, the large deformation predicted by the breakup model for ^{94m}Ag (21^+) remains a puzzle.

Future experiments of our collaboration aim at improving the data on proton–proton correlations by performing decay measurements at the IGISOL facilities at Louvain [13] and/or Jyväskylä [14]. To this end the development of an efficient and element selective laser ion-source has been initiated. The alternative method of studying the ^{94m}Ag (21^+) at a recoil separator is considered at Argonne [15] and Oak Ridge [16]. If combined with detecting γ-ray at the target such experiments will in principle give the chance to identify transitions feeding the (21^+) isomer and thus to probe its shape. However, the small production cross-section of 350 pb makes this indeed a challenging endeavour. Less difficult a task is certainly the improving the spectroscopy of (moderately) high-spin states in ^{93}Pd and ^{92}Rh which would help to clarify the structure of the levels populated in $1p$ and $2p$ decay of ^{94m}Ag (21^+). Relevant results may even be obtained without new measurements but by inspecting the in-beam data taken when investigating neighbouring nuclei in this region. Thus corresponding ^{93}Pd and ^{92}Rh spectroscopy may be improved by revisiting data taken in earlier in-beam experiment on, *e.g.*, ^{93}Rh [17] and ^{93}Pd [5], respectively.

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